

# The role of the quiet eye in golf putting

**Don Hyung Lee**

Submitted by Don Hyung Lee to the University of Exeter as a thesis for  
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## ABSTRACT

It has been consistently shown in the literature that when gaze is directed to a specific location, for a long enough duration, at the correct time relative to the motor execution, high-levels of performance are possible. In recent years, a particular gaze called quiet eye (QE) has gained growing attention among researchers investigating aiming tasks and has become accepted within the literature as a measure of optimal attentional control. Previous studies consistently displayed that longer QE is associated with superior performance however there is lack of understanding *how* QE exerts its positive effect on performance. Therefore the overriding aim of the current program of research was to explore the mechanisms behind the QE by experimentally manipulating the separate aspects of the QE definition in ways that have not been explored by previous researchers. In study 1 (Chapter 2), two experiments were conducted to examine the key characteristics of the QE in golf putting; duration and location. Novice participants were randomly allocated to training groups of experimentally longer or shorter QE durations (experiment 1) and training groups of different QE locations (experiment 2). A retention-pressure-retention design was adopted, and measures of performance and QE were recorded. All groups improved performance after training and the levels of performance achieved were robust in a pressure test. However there were no significant group effects. Study 1 provided partial support for the efficacy of QE training, but did not clarify how the QE itself underpins the performance advantage revealed in earlier studies and suggested that the QE should perhaps not be reported simply as a function of its duration or its location. In study 2 (Chapter 3) an examination of the *timing* of the QE was performed, using an occlusion

paradigm. This provided an experimental manipulation of the availability of visual information during the putting action. Expert participants performed a putting task under three different conditions, namely full, early, and late vision conditions. The results showed that putting accuracy was the poorest when late visual information was occluded (early vision condition). Therefore study 2 suggested that the correct temporal placement of gaze might be more crucial to successful performance, and that putting accuracy was poorer when the latter component of QE which ensures precise control of movement was occluded. Previous research has revealed that anxiety can attenuate the QE duration, shortening the latter component which was shown to be important in study 2. Therefore the final study in the thesis examined the influence of anxiety on attentional control (QE). Expert golfers participated in a putting shootout competition designed to increase levels of anxiety and continued putting until a missed putt occurred. The results revealed that duration of QE was shorter on the missed putt, while there was no difference in QE duration for successful putts (first and penultimate putts). The results are therefore supportive of the predictions of attentional control theory. Furthermore this reduction in QE duration was result of latter component of QE being attenuated, supporting models of motor control that point to the importance of online visual information for regulating control of movements. The results of this series of studies conclude that the timing of the QE – maintaining a steady fixation through the unfolding movement to ensure precise online control - seems to be the strong candidate for how QE exerts a positive effect on performance.

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## Table of Contents

<b>LIST OF TABLES .....</b>	<b>8</b>
<b>LIST OF FIGURES.....</b>	<b>9</b>
<b>Research Papers .....</b>	<b>11</b>
<b>Chapter 1. Introduction.....</b>	<b>12</b>
<b><u>1.1. Quiet Eye</u> .....</b>	<b>13</b>
<b><u>1.2. QE Mechanisms</u> .....</b>	<b>14</b>
<u>1.2.1. Pre-programming</u> .....	15
<u>1.2.2. Online control</u> .....	17
<b><u>1.3. QE, expertise &amp; performance</u> .....</b>	<b>19</b>
<b><u>1.4. QE &amp; anxiety</u>.....</b>	<b>20</b>
<b><u>1.5. QE training</u> .....</b>	<b>23</b>
<b><u>1.6. Scope &amp; outline of the thesis</u> .....</b>	<b>26</b>
 <b>Chapter 2 (Study 1): What Drives Quiet Eye Training Effects? An</b>	
<b>Examination of Visuomotor Control Processes.....</b>	<b>29</b>
<b><u>2.1. Introduction</u>.....</b>	<b>29</b>
<b><u>2.2. Experiment 1</u> .....</b>	<b>33</b>
<u>2.2.1. Methods</u> .....	34
<u>2.2.2. Results</u> .....	39
<u>2.2.3. Discussion</u> .....	42
<b><u>2.3. Experiment 2</u> .....</b>	<b>44</b>
<u>2.3.1 Methods</u> .....	45
<u>2.3.2. Results</u> .....	49
<u>2.3.3. Discussion</u> .....	53
<b><u>2.4. General Discussion</u> .....</b>	<b>55</b>

<b><u>2.5. Conclusions</u></b> .....	<b>59</b>
<b><u>2.6. Directions For Future Research</u></b> .....	<b>59</b>
<b>Chapter 3 (Study 2): An Occlusion Paradigm to Assess the Importance of the Timing of the Quiet Eye Fixation.</b> .....	<b>61</b>
<b><u>3.1. Introduction</u></b> .....	<b>61</b>
<b><u>3.2. Methods</u></b> .....	<b>64</b>
<b><u>3.3. Results</u></b> .....	<b>68</b>
<b><u>3.4. Discussion</u></b> .....	<b>71</b>
<b><u>3.5. Conclusions</u></b> .....	<b>75</b>
<b><u>3.6. Directions For Future Research</u></b> .....	<b>76</b>
<b>Chapter 4 (Study 3): Quiet Eye and Choking: Online Control Breaks Down at the Point of Performance Failure</b> .....	<b>77</b>
<b><u>4.1. Introduction</u></b> .....	<b>77</b>
<b><u>4.2. Methods</u></b> .....	<b>82</b>
<b><u>4.3. RESULTS</u></b> .....	<b>86</b>
<b><u>4.4. DISCUSSION</u></b> .....	<b>88</b>
<b><u>4.5. Conclusion</u></b> .....	<b>94</b>
<b><u>Chapter 5. General Discussion</u></b> .....	<b>96</b>
<b><u>5.1. Summary and implications</u></b> .....	<b>96</b>
<u>5.1.1. QE training</u> .....	96
<u>5.1.2. Influence of QE duration and location</u> .....	98
<u>5.1.3. Pre-programming and online control</u> .....	101
<u>5.1.4. Influence of anxiety on visual attention</u> .....	104
<u>5.1.5. Theoretical and practical implications.</u> .....	107
<b><u>5.2. Limitations and Directions for Future Research</u></b> .....	<b>112</b>

<b><u>5.3. Final conclusion</u></b> .....	<b>114</b>
<b><u>References</u></b> .....	<b>115</b>
<b><u>Appendices</u></b> .....	<b>129</b>

## **LIST OF TABLES**

	<b>Page</b>
<b>Chapter 2: Study 1</b>	
Table 2.1: Mean (SD) Cognitive anxiety for the Short and Long QE groups during baseline, retention tests, and pressure test.....	40
Table 2.2: Putting instructions provided to all three groups. Note that only the location of final QE fixation differs: on the ball for the Ball group; on a 'paper' ball 45cm closer to the hole on the line of the putt for the Front group; and on a 'paper' ball set 45 cm away from the participant, perpendicular to the line of putt.....	47
Table 2.3: Mean (SD) Cognitive anxiety for the Ball and Front QE groups during baseline, retention tests, and pressure test.....	50
Table 2.4: Mean (SD) putter kinematic variables for the Ball and Front groups in Baseline and Retention conditions.....	53
<b>Chapter 3: Study 2</b>	
Table 3.1: Mean (SD) putter kinematic variables for control, early vision and late vision conditions.....	71
<b>Chapter 4: Study 3</b>	
Table 4.1: Mean $\pm$ SD duration (ms) of the preparation, backswing, and foreswing phases of the first, penultimate, and final putts of the shootout task.....	87



## **LIST OF FIGURES**

	<b>Page</b>
<b>Chapter 2: Study 1</b>	
Figure 2.1: A schematic of the timing of instructions delivered by the audio recordings for Short and Long QE duration groups.....	36
Figure 2.2A: Mean QE duration (ms) for the Short and Long groups at baseline, retention and pressure tests.....	41
Figure 2.2B: Mean (SE) radial error (cm) for the Short and Long groups at baseline and retentions and pressure tests.....	42
Figure 2.3A: Mean (SE) QE duration (ms) for the Ball and Front groups at baseline, retention, and pressure tests.....	51
Figure 2.3B: Mean (SE) radial error (cm) for the Ball and Front groups at baseline and retention test.....	52
<b>Chapter 3: Study 2</b>	
Figure 3.1: A diagram of the experimental set up showing key elements of the occlusion method: a) Infra-red reflector; b) Liquid Crystal SmartGlass; c) Infrared sender.....	66
Figure 3.2A: Mean (SE) QE duration (ms) for control, early vision and late vision conditions.....	69
Figure 3.2B: Mean (SE) radial error (cm) for control, early vision and late vision conditions.....	70

**Chapter 4: Study 3**

Figure 4:      Mean  $\pm$  SEM duration of the prep-rogramming (QE-pre), online control (QE-online), and dwell (QE-dwell) components of the overall QE duration (QED; sum of the three subphases) for the first, penultimate, and final putts of the shootout..... 88

**Chapter 5: General discussion**

Figure 5:      Hypothesised multiple processing events associated with single golf putt.....110

## **Research Papers**

Chapter 4: Vine, S.J., Lee, D., Moore, L.J., & Wilson, M.R. (2013). Quiet eye and choking: Online control breaks down at the point of performance failure.

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An occlusion paradigm to assess the importance of the timing of the quiet eye fixation. *European Journal of Sports Sciences*.

Chapter 2. Lee, D., Vine, S.J., & Wilson, M.R. (in prep). What drives quiet eye training effects? An examination of visuomotor control mechanisms. *Journal of Applied Sport Psychology*.

## **Chapter 1. Introduction**

In order to produce accurate goal-directed movements, the motor system requires accurate and timely visual information about targets critical to task completion. For example, as shown in Land and colleagues' work (1999) in tea-making, in order to boil water our gaze is first oriented to the kettle to locate the handle and then to the sink, where water will be filled up, while followed by the actions of grabbing the kettle and moving towards the sink respectively. After this, gaze is directed to the water tap and back to the kettle to monitor the level of water being filled. When filling of water is completed gaze is directed to the stove where the kettle will be placed. This example illustrates how visual information is tightly coupled with motor action.

While the timely acquisition of visual information in everyday-tasks is important, it is even more critical in sport where accurate performance must be achieved under extremely high temporal and spatial demands and often under high levels of pressure. Therefore, researchers have been interested in how vision supports accurate sports performance. Much of this research has adopted eye tracking technology, and has shown that during high levels of motor skill performance, gaze is directed to the most salient targets and objects in the visual-performance workspace (e.g. Vickers, 2007). As such there is a strong link between motor skill performance and the gaze control of the performer (See Causer, Janelle, Vickers, & Williams, 2012; Vine et al., 2014 for recent reviews).

In a seminal study, Vickers (1992) investigated the role of gaze control in golf putting. Participants were elite and near elite golfers who had their eye

movements recorded while completing putts from 3m until 10 hits and 10 misses were obtained. It was revealed that elite golfers fixated their eyes on the back of the ball for about two seconds prior to the initiation of the backswing of the putter and maintained this fixation until after putter-ball contact (effectively dwelling on the same location for around 300-500ms after contact). Conversely, near-elite counterparts had a briefer fixation (of 1 to 1.5 seconds). Based on these results, Vickers suggested that a longer gaze fixation on a single location allows superior performance by reducing distractions from other stimuli available throughout the putting action. Since Vickers' seminal study, this last fixation before the initiation of the backswing has been termed "quiet eye" (QE: Vickers, 1996).

In the last 20 years, the QE has gained growing support among researchers investigating aiming tasks, and has become accepted within the literature as an objective measure of optimal attentional control (Vine & Wilson, 2010).

### **1.1. Quiet Eye**

The QE is defined as the final fixation or tracking gaze towards a relevant target in the visuo-motor workspace within 3° of visual angle (or less) for more than 100 ms, which has an onset prior to the initiation of a critical movement and an offset that can occur during or after the movement's completion (Vickers, 2007). It was originally postulated to functionally represent the time needed to organize the neural networks and visual parameters responsible for the orienting and control of visual attention (Vickers, 1996). However recent studies have suggested that the QE can also be considered as a critical period when sensory information is synthesized with the mechanisms necessary to both plan (pre-

programme) and control (online) the appropriate motor response; with the relative weighting of pre-planning and online control functions depending on task specific demands (Wilson, Causer, & Vickers, 2015). For example in rifle shooting where the movement time is short, the QE duration reflects pre-programming (Janelle et al., 2000), whereas in golf putting, the QE appears to provide both pre-programming (Mann, Coombes, Mousseau, & Janelle, 2011) and online control (Oudejans, van de Langenberg, Hutter, 2002; Craig, Delay, Greal, and Lee, 2000) functions.

## **1.2. QE Mechanisms**

Studies have recently attempted to explain the mechanism behind QE in terms of both cognitive and ecological psychology perspectives (de Oliveira, Oudejans, & Beek, 2008; Mann et al., 2011; Oudejans et al., 2002; Williams, Singer, & Frehlich, 2002). Researchers from an ecological psychology (e.g. Oudejans et al., 2002) suggest that QE is a period of time where information regarding the target is continuously collected, thus body movements are continuously adjusted relative to the target information (Oudejans, Koedijker, Bleijendaal, & Bakker, 2005). Indeed research examining kinematic profiles in golf putting suggests that the putting action is continually adjusted on the basis of visual information (Tau) during movement execution (Craig et al., 2000). Therefore QE might have role in supporting this online control of movement – providing the most up-to-date visual information which the motor system can use to self-organise.

Alternatively, cognitive psychologists suggest that QE allows performers an extended duration of response programming, while minimizing distraction from

other environmental cues (Vickers, 2011). Williams et al. (2002) supports this cognitive psychology view of the QE. In their study, they measured QE duration in billiards shots of different complexity and found that a longer QE was associated with more complex shots. Furthermore, when the preparation time for the billiard shot was constrained by 25% and 50% of the typical time taken, performance deteriorated. As longer pre-programming time is required for more complex tasks (Klapp, 1980) the authors argued that degradation of performance was due to reductions in pre-programming (Williams et al., 2002).

### **1.2.1. Pre-programming**

Vickers postulated that fixations of relatively long duration (QE) must be made to specific target locations during the preparatory phase of the movement to program the parameters of the movement (e.g. direction, distance, and force), and the timing and coordination of limbs necessary to produce movement that is required to successfully perform motor tasks (e.g. Vickers, 1996; Williams et al., 2002). In her seminal study of basketball free throw shooting, Vickers (1996) showed that elite free throw shooters fixate the basket for a longer duration before the initiation of the movement and this fixation terminated at the initiation of the extension phase of the throw. When adequate pre-programming was achieved they suppressed their vision, by blinking or moving their gaze freely during the shooting action. Vickers contended that once pre-programming had been completed, attention is freed up while the ball blocks the target, emphasizing a pre-programming role for QE.

Another possible support for the pre-programming role of QE might be found from the study by Mann et al. (2011). They examined specific neural

mechanisms that might help elucidate proficiency-based differences in QE durations in a golf putting task. Specifically, they found that QE duration was closely associated with the Bereitschaftspotential (BP) - a pre-motor readiness potential. BP is a negative potential that precedes an actual, intended, or imagined event by 1-1.5 s which has a visually distinct waveform comprised of three components; BP<sub>early</sub>, BP<sub>late</sub>, and BP<sub>peak</sub>. The authors inferred that the QE period serves an important preparatory motor programming function and allows time for the brain to coordinate neural structures involved in movement preparation (Mann et al., 2011).

Recently Klostermann, Kredel, and Hossner (2013) directly manipulated the duration of QE during underhand throwing task. Participants were trained to learn the throwing action. In order to introduce QE duration as an independent variable, the movement phases were paced by beeps. In the first experiment, participants underwent training with the target presented on the screen that appeared at the one of four corners and jumped to one of two positions; 3 and 12 o'clock positions, under two different presentation time, short presentation (SP) and long presentation (LP), which was designed to manipulate the duration of QE. After the training, participants' throwing accuracy were tested. The results showed that throwing accuracy for LP condition was better compared to SP. In the second experiment, 4 different conditions were tested, low task demand with SP and high task demand condition with LP. In low task demand, the predictability of target position was 100%; appeared at the bottom left corner and jumped to 12 o'clock position, while high task demand condition had lower predictability of the final target position; appeared at one of remaining three corners and then jumped to either the 9 or 6 o'clock position. The result



showed that effect of QE duration on throwing accuracy was only existed when the task demand was high; throwing accuracy was better at the LP compared to SP in high task demand condition while SP and LP in low task demand had similar performance. Based on these findings, the authors concluded that there might be a causal relationship between QE duration and performance that longer QE duration provides superior performance. However, the authors also acknowledged that this relationship was only evident when the demand for information processing was high; no performance advantage for LP over SP during low task demand condition supporting Williams et al. (2002) that the performance-enhancing effects of longer QE depend on the amount of information to be processed (Klostermann et al., 2013).

### **1.2.2. Online control**

Contrary to Vickers' contention, Oudejans and colleagues (de Oliveira, Oudejans, & Beek, 2006; Oudejans et al., 2002) have suggested that performers in basketball jump shooting prefer to use late visual information to guide performance. For example, the authors examined how performance is affected when vision of the hoop during part of the jump shot is occluded. Expert basketball players were put into 4 different conditions of jump shooting; namely an early vision condition, where vision was occluded during the shooting movement after the ball had been moved past the line of gaze; a late vision condition, where vision was occluded after initiation of the trial until the ball was moved past the line of gaze; a full vision condition, where vision was not occluded, and a no-vision condition, where the vision was occluded during the entire execution of the task. The results revealed that the shooting percentage was not affected when early vision - where pre-programming

presumably occurs - was occluded compared to full vision condition. However, occlusion of late vision - where online control occurs - severely impaired performance. Therefore, the authors argued that basketball jump shooting requires online processing of visual information to make up-to-date corrections to the final movements, rather than pre-programming. However, the authors also acknowledged that this was the case for only high-style shooters (who re-fixate the basket once the ball is overhead), and the results for low-style shooters (who shoot with the ball in front of the face) were in the direction of what Vickers suggested. In effect Oudejans et al. suggest that individuals use the latest possible information that is available to them.

A subsequent study by de Oliveira et al. (2006) further argued that shooters prefer late information pick-up regardless of shooting style. In that study, using intermittent viewing techniques, both high and low style shooters performed basketball jump shots. Both groups relied on the late viewing of the basket, high style (just before the ball release) and low style (just before the hands and the ball interfere the viewing of the basket), and the shooting performance was not significantly different when compared to the full vision condition reported by Oudejans et al. (2002). In the follow-up study, long fixations were not possible, due to the intermittent viewing conditions. Therefore, this result supports the contention that late information pick up during the movement is critical for successful performance. The importance of longer QE durations per se, which have been shown to be characteristic of superior performance, might need to be revisited. Perhaps the timing of the long fixation (early or late in movement preparation) might be more important than its duration? If, as Oudejans and colleagues suggest, the QE serves an online control function, then the latter

component of the QE might be more critical than the earlier (pre-programming) component.

### **1.3. QE, expertise & performance**

Although the mechanisms behind the benefits of the QE remain unclear, studies have consistently shown the advantage of a longer QE. A number of studies have examined differences in the duration of QE between experts and non-experts, and found that experts have longer QE compared to non-experts (see Mann, Williams, Ward, & Janelle, 2007 for a meta-analysis; and Vickers, 2011; Causer et al., 2012; Vine et al., 2014, for recent reviews). Janelle et al. (2000), in a study examining the gaze behaviour of expert and non-expert rifle shooters, showed that experts displayed longer QE and superior performance compared to non-experts. Furthermore, Williams et al. (2002) found QE differences between skilled and less skilled billiards player. The QE duration of skilled billiards players were significantly longer than their unskilled counterparts. From a cognitive processing perspective, experts have learned to extend the QE to process critical information that is required for higher-level performance (Vickers, 2009).

QE differences are not only limited to the level of expertise, but also underlie intra-individual performance variability, e.g., holed putt vs. missed putt in golf, successful shot vs. unsuccessful shot in billiards, (Panchuk & Vickers, 2006; Piras & Vickers, 2011; Vickers, 2007; Williams et al., 2002; Wilson & Percy, 2009). It has been consistently shown in the literature that the QE is longer for successful performance outcomes (hits) than unsuccessful outcomes (misses). For example in a study examining gaze behaviours of straight and breaking

putts, Wilson and Percy (2009) found that participants had significantly longer quiet eye periods on successful putts (1693ms) than on unsuccessful putts (1231ms). Furthermore, Behan and Wilson (2008) examined the QE duration of novices during the performance of a simulated archery task and found that successful attempts were associated with longer QE durations compared to unsuccessful attempts. Panchuk and Vickers (2006) showed that ice hockey goaltender displayed longer QE duration on saves compared to goals. Williams et al. (2002) also found that successful shots in billiards were associated with longer QE durations. Therefore, a growing body of research has consistently found that a longer QE duration is not only associated with expertise (inter-individual differences), but also superior performance (intra-individual differences).

#### **1.4. QE & anxiety**

The relationship between state anxiety and QE is also becoming well established in the literature. It is suggested that state anxiety is an aversive emotional state that occurs as a result of threat and is related to the subjective evaluation of a situation with regard to one's self esteem (Eysenck & Calvo, 1992). Previous studies have shown that goal directed attentional control indexed by QE is susceptible to change under the influence of anxiety (Behan & Wilson, 2008; Vickers & Williams, 2007; Vine & Wilson, 2010; 2011; Wilson, Vine, & Wood, 2009a; Wilson, Wood, & Vine, 2009b). For example, in a simulated archery task Behan and Wilson (2008) found that the QE duration of participants was significantly shorter in a high-pressure condition compared to a lower pressure condition, leading to poorer performance. Wilson et al. (2009a), in a basketball free throw study, also found reductions in QE during a high

threat condition compared to a control condition. These results are in line with Janelle's (2002) proposal that the QE reflects the efficiency of visual attention and is sensitive to threat.

Attentional control theory (ACT; Eysenck, Deraksham, Santo, & Calvo, 2007) has been adopted as a theoretical framework to explain how anxiety affects the QE and subsequent performance. ACT is the successor of processing efficient theory (PET; Eysenck & Calvo, 1992), which posited that anxiety impairs the efficiency of the central executive of working memory potentially leading to performance degradation. ACT extended PET by specifying how anxiety affects lower level functions of the central executive of working memory (Baddeley, 1986). ACT predicts that the effects of anxiety on attentional process are of fundamental importance in order to understand how anxiety influences performance (Eysenck et al., 2007). When anxious, attention is allocated to detect the source of the threat and deciding how to respond, leading processing resources to be diverted away from task-relevant stimuli and toward task-irrelevant stimuli (see Wilson, 2008, 2012 for reviews). This disruption is assumed to be the case irrespective of whether these stimuli are external (e.g. environmental distracters) or internal (e.g. worrying thoughts) (Eysenck et al, 2007; Wilson, 2008).

The impairment in attentional control is postulated to be due to anxiety disrupting the balance between the two attentional systems outlined by Corbetta and Schulman (2002); a goal-directed (top-down) attentional system and a stimulus-driven (bottom-up) attentional system. The goal-directed system is

influenced by expectation, knowledge, and current goals while the stimulus-driven system responds to salient or conspicuous stimuli. Anxiety increases the influence of the stimulus driven attentional system at the expense of the more efficient goal directed system (Eysenck et al., 2007). Therefore it is easier for the performer to be distracted by the task irrelevant stimuli leading attention to be diverted away.

Furthermore, ACT suggests how anxiety adversely affects two functions of central executive; inhibition and shifting functions (Miyake, Friedman, Emerson, Witzki, Howerter, &Wager, 2000). The inhibition function is responsible for inhibiting attention to task irrelevant stimuli while the shifting function is responsible for switching attention between and within tasks (based on Miyake et al., 2000). ACT postulates that the inhibition function and the shifting function of the central executive are impaired under the influence of anxiety. As a result of this impairment, balance between the goal-directed and stimulus-driven attentional systems gets disrupted (Eysenck et al., 2007).

It has been proposed that effective goal-directed attentional control is represented by longer QE duration (with the impact of the stimulus driven attentional system dampened during this period; see Vine & Wilson, 2011). When the balance of these systems is disrupted by anxiety, greater attentional control is allocated to the stimulus driven system, causing attenuation of QE (goal-directed attentional control) duration.

Causer, Holmes, Smith, and Williams (2011a) tested the predictions of ACT by examining the effect of anxiety on attentional control (QE) and subsequent

performance in shotgun shooting. 16 elite shotgun shooters were tested under two anxiety conditions; low and high. The results showed that participants displayed shorter QE, less efficient movement kinematics, and worse performance under the high, compared to low anxiety condition, thus supporting the prediction of ACT. Wilson et al. (2009a) also tested the predictions of ACT by using QE as an objective index of attentional control during basketball free throw. The authors found that anxiety shortened the QE period, as participants took more fixations around the vicinity of the target. It was suggested that anxiety increased stimulus-attentional control, which resulted in attenuation of QE period. Vickers and Williams (2007) examined the effect of anxiety on biathlon performance and found that during pressurised condition biathletes exhibited significantly shorter QE, resulting in decreased performance compared to performance in a non-pressurised condition.

Based on the studies examining anxiety-induced performance, which revealed that anxiety attenuates QE, (e.g., Vickers and Williams, 2007), it has been suggested that training the QE might facilitate optimal attentional control under pressure, thus protecting performance from the adverse effects of increased anxiety (Behan and Wilson, 2008). Such a paradigm would also strengthen the proposal that the QE is an objective measure of attention and plays a causal role in supporting performance under pressure (rather than simply being a by-product of good performance).

### **1.5. QE training**

QE training focuses on teaching performers to adopt the eye movements of an elite prototype and has been shown to have positive impact on learning and

performance (Causer, Holmes, & Williams, 2011b; Harle & Vickers, 2001; Moore, Vine, Cooke, Ring, & Wilson, 2012a; Vine & Wilson, 2010, 2011; Vine et al., 2011). Originally, QE training studies focused on the trainability of already experienced performers. A number of studies have shown that QE is trainable for such a population (Adolphe, Vickers, & Laplante, 1997; Harle & Vickers, 2001). For example, Harle and Vickers (2001) trained a group of elite university basketball players over two seasons and as a result of the training QE was improved as well as the performance compared to the control group who did not receive QE training.

In contrast to these earlier QE training studies, recent training studies have focused on training novice performers and examining whether performance could not only be improved more quickly but also made more robust to the adverse effects of anxiety. For example, in the first such study, Vine and Wilson (2010) examined the effect of QE training on the gaze control and the putting performance of novice participants. 14 participants were randomly assigned to either a QE training group or a control group and performed 40 putts at baseline, 320 acquisition putts, and 120 test putts in a retention-pressure-retention design. The control group received coaching guidance related to the mechanics of the putting stroke while the QE training group received same coaching guidance related to the putting stroke as well as a specific QE training element. The results showed that there were no significant difference in performance between control and QE training groups at retention tests, however the QE trained group performed better in a pressure test compared to the control group. QE data showed that the QE training group improved QE duration significantly at retention tests compared to baseline and maintained



effective QE duration at pressure test. The control group also improved significantly baseline to retention tests however it was still significantly shorter than QE training group and QE duration at the pressure test was significantly reduced compared to the retention test (Vine & Wilson, 2010).

As a follow up study, Vine et al. (2011) examined the effect of QE training in both laboratory and in real putting statistics on the course with experienced golfers. Twenty-two elite golfers were asked to record their putting performance for 10 competition rounds and upon completion of this recording they visited laboratory individually for training. They were randomly assigned into either a QE training or control group. 20 putts were taken for the baseline measure and they began to receive their assigned training regime consist of four blocks of five putts which involved viewing gaze control of elite prototype and their own gaze control, however only QE training group received specific QE-related feedback. Participants were again asked to record their putting performance for 10 competition rounds and return to laboratory to perform 20 retention and 15 pressure putts. The results showed that the QE training group maintained QE duration and performed better in the pressure test than the control group, whose QE duration reduced. The QE training group took 1.9 putts less per round than pre-training while there was no change in the number of putts taken by the control group. Both these golf putting studies indicate that performance can be protected from the adverse effect of anxiety through QE training intervention regardless of skill level.

Taken together, the results of this body of literature suggest that QE training is a simple, but, effective way to improve performance. While there is increasing

support for the efficacy of QE training, there is less empirical explanation about *how* QE works to help performance.

### **1.6. Scope & outline of the thesis**

It has been consistently shown that when gaze is directed to a specific and relevant location, at the correct time relevant to movement, and for a sufficient duration, high-levels of performance can be achieved. Although previous studies, especially by Moore et al. (2012a), have attempted to shed light on the mechanism behind the QE, it is still not clear how exactly QE works in helping performance. Therefore, more critical questions need to be asked about the role of the QE fixation in underpinning accurate performance.

Based on findings from the current literature, the extent to which the QE supports the pre-programming of movements, or the on-line control of movements as they unfold is widely debated. Therefore a goal of this thesis is to explore this tension in the literature in more detail using a golf putting task. The golf putt is a self-paced, targeting task that places interesting constraints on the visuomotor and working memory systems. The visual system must first orient to and process the most salient perceptual cues necessary to ascertain both distance and direction information, then provide online information to guide appropriate putter-ball contact; all while working memory matches stroke length and tempo with the requisite stroke force (Mann et al., 2011; Wilson & Pearcy, 2009).

As shown in the study by Vickers (1992), the gaze of experts is directed to the ball before initiation of backswing (QE-pre) and maintained during (QE-online)

and even after the ball has been struck (QE-dwell). Vickers (2007) suggested that covert attention shifts 100 to 300 ms prior to overt gaze shifts. In effect, if the gaze shifts away from the ball at the time of putter-ball contact (zero QE-dwell), there is a possibility that the covert attention might have shifted away from the ball prior to the putter ball-contact, which may cause poor contact between the putter and the ball. This suggests a possible explanation for the online control (QE-online and QE-Dwell) role of QE in golf putting in addition to the pre-programming role of QE which occurs before initiation of backswing. Therefore, it might be also critical to maintain QE during (QE-online) and after the putting execution (QE-dwell) in order to provide online information to guide accurate and consistent putter-ball contact (Vine, Moore, & Wilson, 2011). The importance of visual control in this task makes it particularly interesting to ask more critical questions related to the role of QE.

Perceptual-cognitive expertise is usually characterised by efficient eye movement strategies (Mann et al., 2007), however a 'longer is better' approach to QE duration appears to perhaps reflect a more *inefficient* solution. While task demands will determine the specific processing needs, there are likely to be both attentional and postural costs of maintaining QE durations beyond any information processing threshold (Behan & Wilson, 2008). Furthermore, there has been much less emphasis on the location and timing of the QE, despite these being important components of the definition. Therefore a key goal of this thesis is to further develop QE theory by experimentally manipulating the separate aspects of the QE definition in ways that have not been explored by previous researchers. The definition of the QE (Vickers, 2007) has three important elements: duration (for how long?), location (where to look?), and

timing (when to look?). Therefore in this thesis we explored the nature of QE by manipulating the duration, and location (Chapter 2), and the timing (Chapter 3) of the QE. Finally, in Chapter 4, I investigated these issues further using an environmental manipulation (i.e. competitive pressure and evaluative threat) that has been predicted to influence these components of the definition. Finally, Chapter 5 (the epilogue), provides a brief summary and synthesis of the main results in this thesis. Theoretical and practical implications are discussed, along with recommendations for future research.

## **Chapter 2 (Study 1): What Drives Quiet Eye Training Effects? An Examination of Visuomotor Control Processes.**

### **2.1. Introduction**

With experience and through training, experts learn to conserve limited cognitive resources and strategically direct their gaze control system to optimise efficient information acquisition and guide accurate goal-directed movement (Land, 2009). A particular gaze strategy, the quiet eye (QE; Vickers, 1996) – the final fixation to a target during the preparation phase of a goal-directed movement – has been the source of recent research interest. The QE is argued to represent a critical period of cognitive processing during which sensory information is synthesized with the mechanisms necessary to both plan (pre-program) and control (online) the appropriate motor response. While longer QE durations have been associated with superior performance across a range of visually guided motor tasks, it is still not clear *how* the QE exerts its effect (Klostermann et al., 2013; Wilson et al., 2015).

Recent studies adopting randomized control intervention designs have provided strong evidence that the QE is likely a causal mechanism rather than a by-product of successful performance. Not only can QE be trained, but this training can have a positive impact on performance – above that of a control group (Causer et al., 2011b; Harle & Vickers, 2001; Moore et al., 2012a; Vine et al., 2011; Vine & Wilson, 2010, 2011). For example, in the first study adopting QE training with novice performers, Vine and Wilson (2010) found that a QE trained group displayed longer quiet eye durations and greater putting accuracy than a

control group in retention and pressure tests. A follow up study (Moore et al., 2012a) found that these performance differences were underpinned by more efficient putter kinematics, greater heart rate deceleration, and reduced muscle activity. The authors suggested that QE training enabled novices to adopt more expert-like visuomotor control of the putting stroke, which they could maintain reliably - even when under pressure.

This explanation for the benefits of QE training is in line with other models of gaze anchoring – with the central nervous system preferring to co-align visual and motor systems in space and time to simplify the computational problem of visually guided movement (Land, 2009; Neggers & Bekkering, 2002; Sailer, Flanagan, & Johansson, 2005). However, a limitation of the QE training literature is that the control groups receive technical (movement-focused) instructions; whereas the QE trained groups receive instructions about their gaze control. While the control group instructions are designed to replicate typical coaching, and therefore provide the ‘standard care’ comparison favored in randomized control trials (Craig, Dieppe, Macintyre, Michie, Nazareth, & Petticrew, 2008), the variance in the information provided to experimental groups makes a clear interpretation of effects difficult.

First, a consistent body of literature (see Wulf, 2013 for a review) has revealed that instructions that promote an external focus of attention (on the movement effect or target) are superior for skill acquisition than those promoting an internal focus of attention (on the movement effectors). The advantage of QE training may therefore be related to differences in attentional focus rather than improved co-alignment of visual and motor systems. Second, given that the QE training

instructions differ from control group instructions in a number of ways, it is difficult to ask more critical questions about the role of the QE fixation in underpinning the performance advantage found for QE trained participants. Indeed, recent research has identified that QE training provides a number of additional benefits (beyond visuomotor improvements), including improved perceptions of control (Wood & Wilson, 2012), more favorable evaluations of heightened stress (Moore, Vine, Freeman, & Wilson, 2013), and advantages linked to implicit motor learning (Vine, Moore, Cooke, Ring, & Wilson, 2013b).

The aim of the current research was therefore to further our understanding of *how* QE supports performance by comparing QE training interventions that are designed to manipulate the key characteristics that define the QE; namely its duration and location. In effect, the 'typical' QE training instructions will now act as the control group while the 'manipulated' QE training instructions will act as the experimental group. From a theoretical perspective, manipulating only QE duration and location, while keeping the rest of the training instructions identical will provide insights into the role of effective motor planning in supporting skill acquisition and performance under pressure. From an applied perspective, it is important to understand *why* interventions work, and despite the consistent success of QE training, the processes supporting its effects are still poorly understood (Vine et al., 2014).

We carried out two experiments in golf putting to explore these aims. The golf putt is a self-paced, targeting task that places interesting constraints on the visuomotor and working memory systems. The visual system must first orient to and process the most salient perceptual cues necessary to ascertain both

distance and direction information, then provide online information to guide appropriate putter-ball contact; all while working memory matches stroke length and tempo with the requisite stroke force (Mann et al., 2011; Wilson & Pearcy, 2009). Since Vickers' (1992) seminal study identified that the duration of the fixation made during the putting action differentiated high and low handicap golfers, golf putting has been frequently used to help further our understanding of the QE phenomenon (e.g., Mann et al., 2011; Moore et al., 2012a; Vine et al., 2011; Vine et al., 2013; Vine & Wilson, 2010; Wilson & Pearcy, 2009). For example, Mann et al. (2011) examined specific neural mechanisms that might help elucidate proficiency-based differences in QE durations in a golf putting task. Specifically, they found that QE duration was closely associated with the Bereitschaftspotential (BP) – a pre-motor readiness potential. The authors inferred that the QE period serves an important preparatory motor programming function and allows time for the brain to coordinate neural structures involved in movement preparation.

The departure point for these experiments was the study by Moore et al. (2012a) which tested the efficacy of QE training for novices performing golf putts from ten feet. The authors found differences in retention test putting performance between groups taught a pre-putt routine focusing on controlling gaze accurately (a QE Training intervention) and one derived from current coaching practices. As predicted, the QE-trained group also revealed longer QE durations; more efficient putting kinematics (less acceleration during the down-stroke); and greater cardiac and forearm electromyographic deceleration in the seconds preceding putter-ball contact. However, additional analyses revealed that only differences in putter acceleration mediated group differences in putting



performance. As group differences in QE duration did not mediate group differences in performance, the study could not provide conclusive support for a causal role for the QE in supporting performance. The authors suggested that a threshold explanation might explain the lack of a monotonic relationship between performance and QE duration – as long as the QE is long enough, it does not need to be any longer (Moore et al., 2012a). An interesting question to pursue is therefore if differences in performance could be found if training groups' instructions differed only in the duration of the final fixation – with a control group taught a 'standard' QE duration, and the experimental group taught a QE duration of below a suggested threshold derived from previous QE training studies (Moore et al., 2012a; Vine et al., 2011; Vine & Wilson, 2010).

## **2.2. Experiment 1**

The aim of the experiment 1 was to manipulate QE duration within a QE training intervention paradigm. If QE duration is a causal mechanism that supports preparatory motor programming (Mann et al., 2011) then a long QE group should perform better after training. This hypothesis is supported by Klostermann et al.'s (2013) recent study that manipulated QE duration in a throwing task using a projected target. Radial error was significantly less in the long QE duration trials, suggesting that QE serves not just as a by product of superior performance but plays a functional role (Klostermann et al., 2013). We therefore hypothesized that participants in our long QE group would reveal lower radial error, and longer QE durations in retention tests, compared to the short QE group. Given that increased anxiety has been shown to negatively impact upon both QE durations and radial error in golf putting (Moore et al., 2012a; Vine et al., 2011; Vine et al., 2013; Vine & Wilson, 2010) we also

predicted that differences would be more pronounced in a pressure test condition (heightened anxiety).

### **2.2.1. Methods**

#### **Participants**

Twenty one undergraduate students (Mean age, 22.71, SD = 2.81 years) volunteered to participate in the study. All participants declared having no official golf handicap or prior formal golf putting experience and thus, were considered novice golfers. Furthermore, all were right-handed, reported normal or corrected vision, and were individually tested. Participants were randomly assigned into one of two QE training groups, which differed only in terms of the final QE duration (eleven in the short, and ten in the long group). The protocol was approved by the local ethics committee and written informed consent was obtained from each participant.

#### **Procedure**

The baseline, training, test phases took place over 2 days and involved taking 420 straight putts from three, 10 ft (3.05 m) locations to a regulation hole (diameter = 10.80 cm) on a relatively fast-running artificial putting green (length = 6 m, width = 2.5 m). All participants used a standard length (90-cm) steel-shafted blade style golf putter (Sedona 2, Ping, Phoenix, AZ) and regular-size (diameter = 4.27 cm) white golf balls. Participants attended individually and on day 1 they first provided written informed consent after reading the study information sheet. Participants wore an Applied Science Laboratories (ASL; Bedford, MA, USA) mobile eye tracker and after calibration, took 10 practice

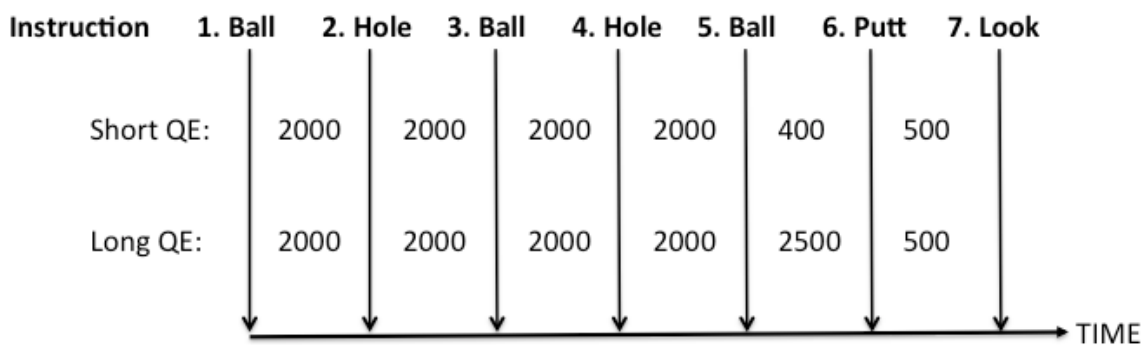
putts. Participants then took 40 putts in a baseline (pretest) condition while the dependent variables of interest were measured. After a short rest period, participants began their respective QE training regime (short or long; see Training Protocol) and performed an additional five blocks of 40 putts, with rest periods provided between blocks.

On day two, participants followed a similar procedure, attending individually and being fitted with the eye tracker. Again, ten practice putts were taken, before a final three blocks of 40 training putts were completed. The pre-putt routine for each of the 320 training putts was externally paced via an audio recording associated with the assigned group (see training protocol below). Finally, participants took 20 putts in a retention 1, pressure, retention 2 condition, without the aid of the audio recording (to match the baseline condition) to form an A-B-A (retention-pressure-retention) design (Vine & Wilson, 2010) before being thanked and debriefed about the purpose of the study. Calibration of the eye tracker was checked every 10 putts to ensure point-of-gaze was being accurately recorded.

### **Training protocol**

Participants were first played an audio recording relevant to their group and had the meaning of each of the seven, single word instructions explained to them. Both audio recordings directed fixations and saccades between the ball and the hole in order to replicate the instructions provided verbally in previous research (Moore et al., 2012a; Vine & Wilson, 2010) study. The only difference between each group's audio recordings was the duration of the final (QE) fixation on the ball before the instruction to putt (see Figure 2.1). In order to maintain a steady

QE fixation during the entire putting phase, participants were instructed to only look up to follow the ball on the “look” instruction. The delay between initiating the putt and looking up towards the hole was derived from pilot testing in order to ensure that all participants would maintain a fixation on the ball throughout the putting stroke<sup>1</sup>.



*Figure 2.1. A schematic of the timing of instructions delivered by the audio recordings for Short and Long QE duration groups.*

## Pressure Manipulation

In keeping with similar previous research (Vine & Wilson, 2010; Moore et al., 2012a) several techniques were used to create social comparison and evaluative threat, which are known to increase levels of cognitive anxiety (Baumeister & Showers, 1986). First, a competition was created and participants were informed that the best performing individual would receive a £50 (\$75) cash reward. Second, participants were told that their performance would be compared with others taking part and will be posted on the social network. Finally, noncontingent feedback was used, whereby participants were

<sup>1</sup> The times displayed in Figure 2.1, are not the times of the resultant QE durations. Pilot testing established that these timings of instructions would create shorter and longer QE duration.

informed that their previous 20 putts (retention test 1) would place them in the bottom 30% when compared to those who had already taken part. They were instructed to try and improve upon their performance; otherwise their data would be of no use for the study.

## **Measures**

**Cognitive anxiety.** Cognitive anxiety was measured at four time points (baseline and each test phase) using the Mental Readiness Form 3 (MRF-3; Krane, 1994) to assess the effectiveness of the pressure manipulation (see procedure). The MRF-3 has three, bipolar, 11-point Likert scales that are anchored between not worried – worried for the cognitive anxiety scale; not tense – tense for the somatic anxiety scale; and not confident – confident for the self-confidence scale. As with other research examining the influence of worry on expert golfers' putting performance, the cognitive anxiety subscale was of main interest (e.g., Wilson, Smith & Holmes, 2007; Vine & Wilson, 2010; Wilson et al. 2010).

**QE duration.** An Applied Science Laboratories (ASL; Bedford, MA, USA) Mobile Eye Tracker incorporated with a laptop (Lenovo R500 ThinkPad) installed with Eyevision (ASL) recording software was used to measure and record momentary gaze (at 30 Hz). A circular cursor (representing 1° of visual angle with a 4.5 mm lens) indicating the location of gaze in a video image of the scene (spatial accuracy of  $\pm 0.5^\circ$  visual angle; 0.1° precision) was recorded for offline analysis. The laptop and recording devices were placed on a desk behind the participant to minimize distraction. The quiet eye duration was operationally defined as the final fixation towards the ball prior to the initiation of

the backswing (Vickers, 2007). A fixation was defined as a gaze maintained on an object within 1° of visual angle for a minimum of 100ms. Quiet eye onset occurred before the backswing and quiet eye offset occurred when the gaze deviated off the fixated object by 1° or more, for greater than 100 ms (Moore et al., 2012a). Gaze data was analyzed using Quiet Eye Solutions software ([www.QuietEyeSolutions.com](http://www.QuietEyeSolutions.com)). This software allows for frame-by-frame coding of both the motor action (recorded from the Mobile Eye's scene camera at 30 Hz) and the gaze of the performer, and automatically calculates quiet eye duration. Consistent with previous studies (e.g., Moore et al., 2012a; Vine & Wilson, 2010), a subset of putts—every fourth for baseline and every second for retention (10 putts per test)—were selected for frame-by-frame video analysis: a total of 420 putts. A second analyst blindly scored 10% of the codeable trials (1 from each participant) and inter-rater reliability was assessed using the interobserver agreement method (Thomas & Nelson, 2001). This analysis revealed a satisfactory level of agreement at 92.9% (Moore et al., 2012a).

**Performance.** Mean radial error (the average distance the ball finished from the hole in cm) was recorded as the most relevant measure of putting performance (as Cooke et al., 2010; Moore et al., 2012a). The experimenter took photographs of the final ball location using a remote control for a Logitech Web Cam mounted directly above the hole, enabling radial error to be calculated offline using computer software (Neumann & Thomas, 2008). Unfortunately, the viewing field was limited by the height that the camera was mounted above the green (viewing field = 1.13 m). Subsequently, on 142 occasions in the baseline condition and 22 occasions in the retention condition, the ball came to rest outside the viewing field of the camera and radial error was then measured

using a tape measure.

**Statistical analysis.** Cognitive anxiety, QE duration and mean radial error were subjected to 2 (Group) x 4 (Test) mixed design ANOVA. If sphericity assumptions were violated the Greenhouse-Geisser corrections were applied, and uncorrected degrees of freedom are reported along with the corrected probability values and the epsilon value. Significant main, interaction, and group effects were followed up with least significant difference (LSD) post hoc t tests. Effect sizes were calculated using partial eta squared ( $\eta_p^2$ ) for omnibus comparisons.

### **2.2.2. Results**

#### **Anxiety**

ANOVA revealed that there was a significant main effect for condition,  $F(3,57) = 19.06$ ,  $p < .001$ ,  $\epsilon = .75$ ,  $\eta_p^2 = .50$ , but no group,  $F(1,19) = .05$ ,  $p = .824$  or interaction,  $F(3,57) = .70$ ,  $\epsilon = .75$ ,  $p = .701$  effects. Both groups had significantly higher anxiety at pressure test compared to baseline and retention tests (all  $ps < .000$ ), and significantly lower anxiety at retention test 2 compared to retention test 1 and pressure test (all  $ps \leq .003$ ) (see Table 2.1).

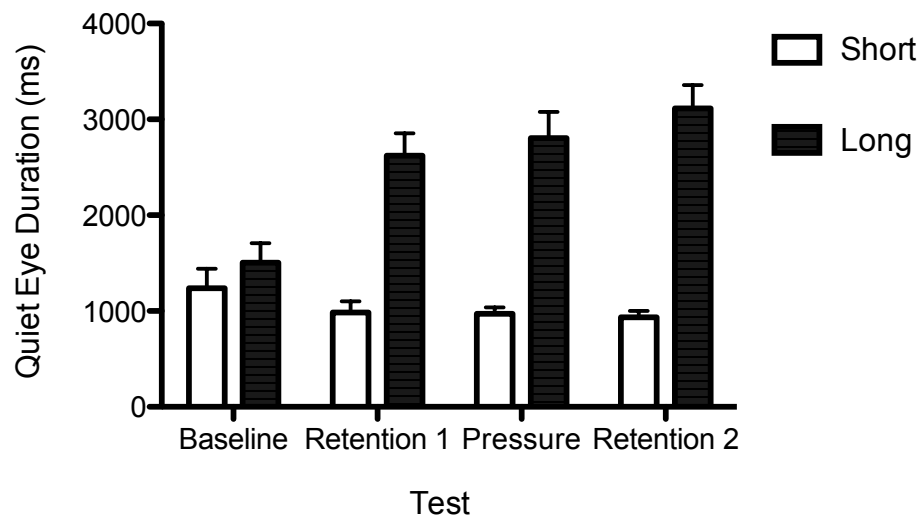
*Table 2.1. Mean (SD) Cognitive anxiety for the Short and Long QE groups during baseline, retention tests, and pressure test.*

	Baseline		Retention 1		Pressure		Retention 2	
	Short	Long	Short	Long	Short	Long	Short	Long
Cognitive anxiety (1-11)	2.70 (2.26)	2.27 (1.49)	2.80 (1.62)	2.91 (1.30)	4.90 (2.18)	5.45 (1.97)	1.90 (1.10)	2.09 (1.14)

### **QE duration**

ANOVA revealed that there were significant main effects for condition,  $F(3,57) = 7.37$ ,  $\xi = .49$ ,  $p = .005$ ,  $\eta_p^2 = .28$ , and group,  $F(1,19) = 47.06$ ,  $p < .001$ ,  $\xi = .49$ ,  $\eta_p^2 = .71$ , and a significant interaction effect,  $F(3,57) = 16.29$ ,  $\xi = .71$ ,  $p < .001$ ,  $\eta_p^2 = .46$ . Follow up tests on the significant interaction effect revealed that there were no QE duration differences between the groups at baseline ( $p = .370$ ), however, the Long group displayed significantly longer QE durations than Short group in the retention tests and pressure test (All  $ps < .001$ ). Within-group analyses revealed that the QE duration of the Long group was significantly longer at retention and pressure than baseline ( $ps \leq .003$ ), but did not significantly change for the Short group ( $p = .241$ ). Anxiety did not affect QE duration of both groups. QE duration data are presented in Figure 2.2A.

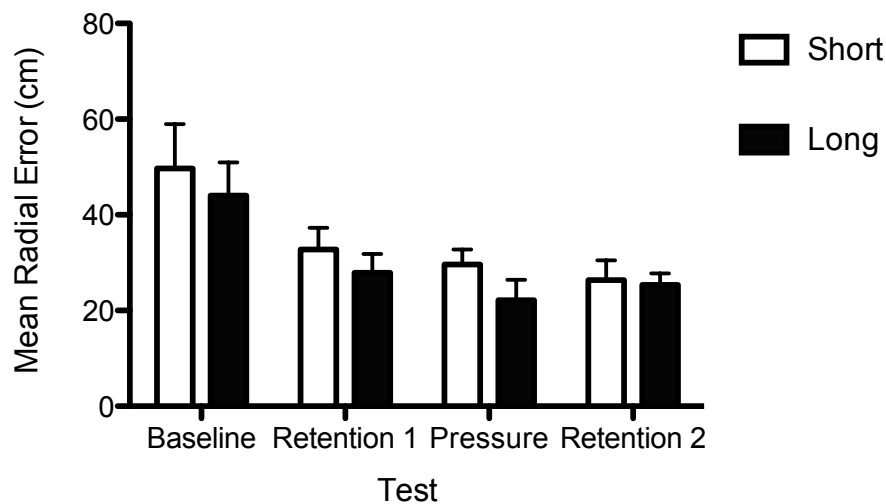




*Figure 2.2A. Mean QE duration (ms) for the Short and Long groups at baseline, retention and pressure tests.*

## Performance

ANOVA revealed that there was a significant main effect for condition,  $F(3,57) = 17.64$ ,  $\epsilon(57) = 1$ ,  $p < .001$ ,  $\eta_p^2 = .48$ , but no group,  $F(1,19) = .60$ ,  $p = .448$  or interaction,  $F(3,57) = .33$ ,  $\epsilon = .56$ ,  $p = .684$  effects. Both groups had significantly better performance after training and maintained performance at retention test levels in the pressure test (see Figure 2.2B).



*Figure 2.2B. Mean (SE) radial error (cm) for the Short and Long groups at baseline and retentions and pressure tests.*

### **2.2.3. Discussion**

In experiment 1, participants followed one of two QE training interventions that differed only in the duration of final QE fixation, which was manipulated using instructions delivered via an audio recording. We predicted that, if QE duration is a key driver of QE training effects, then the Short group would reveal poorer performance than the Long group and this effect would be most pronounced under pressure. The manipulations of QE duration successfully created two groups with significantly different QE durations after training (Figure 2.2A). The pressure manipulation was also successful in that we significantly raised the anxiety levels of both of the groups (Table 2.1). Surprisingly however, there was no interaction effect for the performance data, suggesting that both training regimes were equally as effective (Figure 2.2B).

The results are therefore at odds with the recent findings of Klostermann et al.

(2013) and our hypothesis that a group taught to have shorter pre-programming QE durations would be less accurate in retention and pressure tests. This suggests that the benefits of QE training can be achieved, irrespective of the duration of the QE fixation. There are a number of potential reasons for this. First, the ten foot putting task may not have been difficult enough to have required additional processing resources via longer QE durations. Klostermann et al. (2013) found that task difficulty interacted with QE duration in their study on throwing; only in a more perceptually demanding condition did longer QE durations mediate performance (see also Williams et al., 2002).

Second, the Short group's QE durations were roughly 1000ms in the post-training tests, rather than the 800ms trained by the audio instructions. Perhaps this was close enough to the threshold for information processing to support accurate performance, especially as recent research suggests that maintaining QE just before and through putter-ball contact is more important than having a long period before putter initiation (Vine, Lee, Moore, & Wilson, 2013). The manipulation used in experiment 1 only influenced the portion of the QE duration that occurs prior to putter movement, and this might explain why training all participants to maintain QE through impact (steps 6 and 7 in Figure 2.1) provided similar performance improvements. Indeed, as all groups fixated the ball, this may have helped them to guide the online control of putter-ball contact (Wilson & Pearcy, 2009). Experiment 2 therefore seeks to manipulate the location of the final QE fixation.

### 2.3. Experiment 2

The second important component of the QE definition is that the fixation is directed to a critical location where the most task-relevant information can be processed (Vickers, 2007). The location of QE fixation in targeting tasks is usually somewhat obvious and indeed other models of visuomotor control suggest that we look at the information needed for immediate task goals (Tatler, Hayhoe, Land, & Ballard, 2011). As it is the ball that must be propelled towards the secondary target of the hole in golf putting, it is not surprising that the ball is the defined target of the QE fixation (Vickers, 2007).

However, although it might seem obvious that a ball fixation is important to guide online control, this might not necessarily be the case. Indeed, recent research by MacKenzie, Foley, and Adamczyk (2011) found that visually fixating the hole, as opposed to the ball, did not affect the quality of impact at the precise moment of putter-ball contact. However, that study relied on kinematic and outcome data only and did not explicitly check for differences in processing via QE that might confound the results. Additionally, anecdotal reports from golfers suggest that they fixate locations other than the ball (e.g., Faxon, 2014) and putting coaches sometimes get golfers to pick a spot in front of the ball to practice rolling the ball towards a target (Stockton, 2010; Stupples, 2014).

To test the postulation that QE needs to be at the right location (to support online control of putter-ball contact; Vine et al., 2013), we again manipulated previous QE training regimes (e.g. Moore et al., 2012a; Vine et al., 2011; Vine &

Wilson, 2010) to include two locations: the ball; and 45cm in front of the ball (in line with the target; REF)<sup>2</sup>. Despite the work of MacKenzie et al., we predicted that participants trained to focus their QE on the ball location would be more accurate and have more efficient putting kinematics, based on both the body of QE research findings, and video evidence of the gaze behaviour of elite golfers. As recent research (e.g., Vine et al., 2013a) has suggested that pressure-induced interruptions to ball-focused gaze at impact can degrade putting performance, we predicted that performance differences would be most pronounced in the pressure test.

### **2.3.1 Methods**

#### **Participants**

Twenty-two undergraduate students (Mean age, 23.32, SD = 2.81 years) volunteered to participate in the study. All participants declared having no official golf handicap or prior formal golf putting experience and thus, were considered novice golfers. Furthermore, all were right-handed, reported normal or corrected vision, and were individually tested. Participants were randomly assigned into one of two QE training groups, which differed only in terms of the final QE location (eleven in each group).

#### **Procedure**

The procedure was identical to experiment 1, except for the way in which the QE training regimes were executed. The training regime was again modified

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<sup>2</sup> Due to practical difficulties in measuring gaze at extended visual angles (i.e. when the participants looked towards the hole) we could not replicate MacKenzie et al.'s study. Instead we selected an advanced target (cf. Stupples, 2014) that still meant that putter-ball contact could not be guided online with foveal vision.

from previous research (Moore et al., 2012a; Vine & Wilson, 2010) but did not use an audio recording to manipulate duration. Instead, participants were taught the pre-putt routine they were to adopt via observation of a video model and verbal explanations (as Moore et al., 2012a; Vine et al., 2011; Vine and Wilson, 2010). First, each group viewed a video of an elite prototype who exhibited the gaze behaviour that they were being taught. The researcher directed participants to the key features of the prototype's gaze control whilst asking questions to elicit their understanding. Second, six specific quiet eye training points were explained (see Table 2.2). The videos and instructions varied only with respect to the location of the final QE fixation. The Ball group were taught to perform a typical QE (on the ball), whereas, the Front group were instructed to have a final QE fixation on a paper print out of a ball which was placed 45 cm in front of the golf ball in line with the hole. Verbal instructions were repeated at the start of each of the eight blocks of putts.

*Table 2.2. Putting instructions provided to all three groups. Note that only the location of final QE fixation differs: on the ball for the Ball group; on a ‘paper’ ball 45cm closer to the hole on the line of the putt for the Front group; and on a ‘paper’ ball set 45 cm away from the participant, perpendicular to the line of putt.*

	Ball Group	Front Group
1.	Assume your stance and ensure your gaze is located on the back of the ball.	Assume your stance and ensure your gaze is located on the back of the ball.
2.	After setting up over the ball, fix your gaze first on the “hole”, then the “ball”, then back to the “hole” and finally back on the “ball”.	After setting up over the ball, fix your gaze first on the “hole”, then the “ball”, then back to the “hole” and finally back on the “paper ball”.
3.	Your final fixation should be a quiet eye on the back of the ball.	Your final fixation should be a quiet eye on the back of the paper ball.
4.	The onset of the quiet eye should occur before the stroke begins and last for 2 to 3 seconds.	The onset of the quiet eye should occur before the stroke begins and last for 2 to 3 seconds.
5.	Ensure you maintain gaze on the ball during and after the putting stroke.	Ensure you maintain gaze on the paper ball during and after the putting stroke.
6.	The quiet eye should remain on the green (where the ball was) for 200 to 300ms after the club contacts the ball.	The quiet eye should remain on the paper ball for 200 to 300ms after the club contacts the ball.

## Measures

**Performance error.** QE duration and cognitive anxiety were measured as in Experiment 1. As we found no significant difference in our outcome performance measure in Experiment 1, we also decided to adopt a more fine-grained measure of performance, related to the way in which the putter was controlled (see Cooke et al., 2010).

**Putting kinematics.** Acceleration of the clubhead in three axes was recorded using a tri-axial accelerometer (LIS3L06AL, ST Microelectronics, Geneva, Switzerland). Acceleration in the X, Y, and Z axes corresponded to lateral, vertical, and back-and-forth movement of the clubhead, which assessed clubhead orientation, clubhead height, and impact velocity, respectively. The signals were conditioned by a bespoke buffer amplifier with a frequency response of DC to 15 Hz. Both accelerometer and amplifier were mounted in a 39 mm x 20 mm x 15 mm plastic housing secured to the rear of the clubhead. A microphone (B5 Condenser, Behringer, Germany) connected to a mixing desk (Eurorack UB802, Behringer, Germany) was used to detect the putter–ball contact on each trial. These signals were digitized at 2500 Hz. A computer program determined clubhead kinematics for each putt from the onset of the foreswing phase of the putting stroke until the point of putter–ball contact. The average acceleration was calculated for the X, Y, and Z axes. The values from all trials were averaged to provide a test mean value for each kinematic variable (cf. Cooke et al., 2010; Moore et al., 2012a).



**Statistical analysis.** Cognitive anxiety, QE duration, mean radial error and kinematic variables were subjected to 2 (Group) x 4 (Test) mixed design ANOVA. If sphericity assumptions were violated the Greenhouse-Geisser corrections were applied, and uncorrected degrees of freedom are reported along with the corrected probability values and the epsilon value. Significant main, interaction, and group effects were followed up with one way ANOVA and least significant difference (LSD) post hoc t tests. Effect sizes were calculated using partial eta squared ( $\eta_p^2$ ) for omnibus comparisons.

### **2.3.2. Results**

Due to problems with gaze calibration of the eye-tracker we had insufficient data for QE analyses for one participant (from the Ball group). Also, due to equipment issues with the accelerometer, we also were unable to analyze the putter kinematic data of three different participants (1 from the Ball group and 2 from the Front group). A second analyst blindly scored 10% of the codeable trials (1 from each participant) and inter-rater reliability was assessed using the interobserver agreement method (Thomas & Nelson, 2001). This analysis revealed a satisfactory level of agreement at 90% (Moore et al., 2012a).

### **Anxiety**

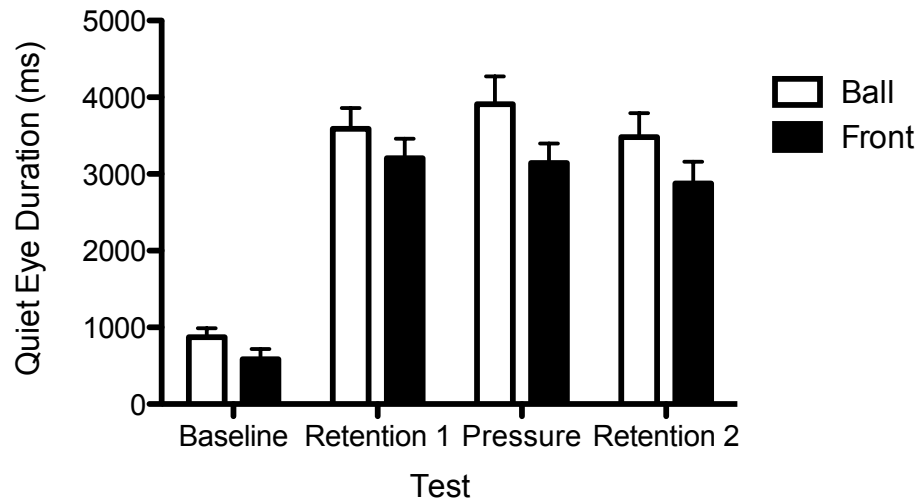
ANOVA revealed that there was a significant main effect for condition,  $F(3,60) = 20.09$ ,  $p < .001$ ,  $\eta_p^2 = .501$ , but no group,  $F(1,20) = .206$ ,  $p = .655$ , or interaction,  $F(3,60) = .972$ ,  $p = .972$ , effects. Both group had significantly higher anxiety at pressure test (see Table 2.3).

*Table 2.3. Mean (SD) Cognitive anxiety for the Ball and Front QE groups during baseline, retention tests, and pressure test.*

	Baseline		Retention 1		Pressure		Retention 2	
	Ball	Front	Ball	Front	Ball	Front	Ball	Front
Cognitive anxiety (1-11)	2.73 (2.10)	3.27 (1.49)	3.18 (2.23)	3.36 (2.66)	6.27 (2.33)	6.36 (2.29)	2.82 (1.60)	3.18 (1.99)

### **QE duration**

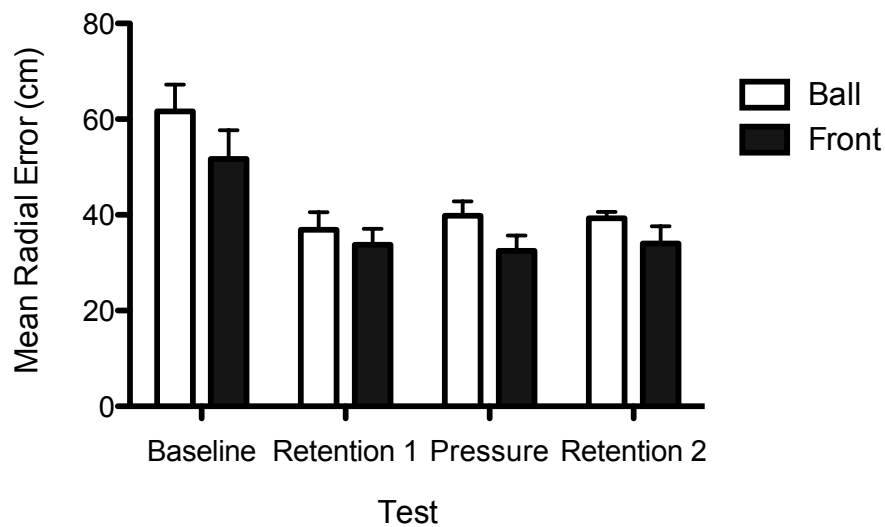
ANOVA revealed a main effect for condition,  $F(3,57) = 82.42$ ,  $p < .001$ ,  $\epsilon = .66$ ,  $\eta_p^2 = .813$ , and the group effect approached significance,  $F(1,19) = 3.72$ ,  $p = .069$ ,  $\eta_p^2 = .164$ . The interaction effect was non-significant,  $F(3,57) = .55$ ,  $\epsilon = .66$ ,  $p = .581$ . Both groups had significantly longer QE durations at retention tests and pressure test compared to baseline (All  $ps < .001$ ) and the Ball group revealed marginally longer QE durations than the Front group. QE duration data are presented in Figure 2.3A.



*Figure 2.3A. Mean (SE) QE duration (ms) for the Ball and Front groups at baseline, retention, and pressure tests.*

### **Performance**

ANOVA yielded a significant main effect for condition,  $F(3,60) = 23.16$ ,  $p < .001$ ,  $\eta_p^2 = .54$ , but no group,  $F(1,20) = 2.37$ ,  $p = .140$  or interaction effects,  $F(3,60) = .46$ ,  $p = .712$ . Both groups had significantly better performance after training (All  $ps < .001$ ) (Figure 2.3B).



*Figure 2.3B. Mean (SE) radial error (cm) for the Ball and Front groups at baseline and retention test.*

### **Putting kinematics**

Kinematic analyses revealed significant condition main effects only for X-axis acceleration,  $F(3,45) = 5.37$ ,  $\epsilon(45) = p = .018$ ,  $\eta_p^2 = .230$ , and Z-axis acceleration,  $F(3,45) = 14.96$ ,  $\epsilon = .230$ ,  $p < .001$ ,  $\eta_p^2 = .45$ . Both groups had lower (more efficient) values for both these kinematic measures after training. There were no other significant main, group or interaction effects (All  $ps > .077$ ). The full kinematic variable results are presented in Table 2.4.

*Table 2.4. Mean (SD) putter kinematic variables for the Ball and Front groups in Baseline and Retention conditions.*

	Baseline		Retention 1		Pressure		Retention 2	
	Ball	Front	Ball	Front	Ball	Front	Ball	Front
x-axis	0.84	1.01	0.62	0.78	.65	.80	.64	.85
acceleration (m.s <sup>-2</sup> )	(0.24)	(0.64)	(0.16)	(0.37)	(.21)	(.38)	(.21)	(.40)
y-axis	1.37	1.29	1.34	1.35	1.34	1.34	1.40	1.38
acceleration (m.s <sup>-2</sup> )	(0.41)	(0.30)	(0.38)	(0.36)	(.34)	(.48)	(.36)	(.43)
z-axis	4.53	4.93	3.14	3.93	3.09	4.03	3.06	4.13
acceleration (m.s <sup>-2</sup> )	(1.26)	(1.08)	(1.13)	(0.75)	(1.23)	(.68)	(1.42)	(.97)

### **2.3.3. Discussion**

Experiment 2 sought to investigate the importance of the location of QE in explaining how QE training might improve performance in golf putting (Moore et al., 2012a). Two groups of novices were trained using modified QE training interventions that differed in the location of the final fixation, but were identical in every other way, including duration. We predicted that the Ball group would putt better (less radial error and more efficient kinematics) than the Front group. We found no group differences in QE durations at Retention and Pressure tests; both groups followed the verbal training instructions (Table 2.2) and lengthened their QE durations (Figure 2.3A) and these were maintained under pressure. However, we also found no group differences in performance (Figure

2.3B) or consistent group differences in putter head kinematics even though they were almost significant (.077 for both Y-axis and Z-axis acceleration) (Table 2.4). Our hypotheses were therefore not supported with regards the functional importance of a spatial alignment between gaze and movement. Instead, the QE training regime enabled all participants to significantly improve and maintain performance and putter control, irrespective of where they fixated their QE.

The finding appears to support the research of MacKenzie et al. (2011) in that the specific location of the final fixation (before and during the stroke) may not be critical for the effective control of a golf putt. From a pre-programming perspective, perhaps any stable QE location provides the necessary quiet period of motor preparation during which the parameters of the movement (e.g., direction and force), as well as the timing and coordination of the limbs, are fine-tuned and programmed. Previous research has suggested that the QE might simply provide a period of general psychomotor quiescence (Vine et al., 2014), in which dampened central and peripheral responses enable more effective fine motor skill performance (e.g., Moore et al., 2012a; Cooke et al., 2014).

Additionally, the visual information required to plan the movement is processed during the entire 'visual routine' (cf. Ballard & Hayhoe, 2009) of both QE training regimes (i.e. the saccades between fixations to the hole and the ball – see step 2, Table 2.2). Therefore, it may not matter that the final fixation is not on the ball, as the direction and force parameters will have already been determined by the fixations made earlier in the routine. This is a prediction that could be explored further in future research.

## **2.4. General Discussion**

The aim of these experiments was to further our understanding of how the QE training ‘works’ to underpin superior performance (see Vickers, 2011). The starting point for the enquiry was the definition of the QE itself and in particular the functional role of QE duration and location with relation to the motor action. We therefore amended QE training instructions from previous research (e.g., Moore et al., 2012a; Vine & Wilson, 2010) to manipulate the duration (experiment 1) and location (experiment 2) of the QE fixation in golf putting.

Results revealed a significant improvement in performance for all groups from baseline to retention tests (both experiments). These are in line with previous training studies, which have shown the positive effect of QE training on performance (Moore et al., 2012a; Vine & Wilson, 2010; Vine et al., 2011). However, the expected performance advantage for a longer QE duration (experiment 1) and ball-focused QE (experiment 2) did not materialize. These findings are therefore suggestive of an advantage for the process of QE training that might be separate to advantages due to the proposed mechanisms of the QE per se.

First, QE training is a pre-shot routine and perhaps it is the routine that improves performance. No differences in these studies were found when only a small part of the routine was changed (compared to when QE training is compared to technical instructions). This finding also points to an attentional focus mechanism – perhaps QE training just ensures that individuals maintain an external focus – and the duration and location of this external focus are not critical. Second, QE training ensures that gaze is stable during the putting

stroke, which might help guide more accurate putter ball contact (even if gaze is not directed to the contact point itself). Indeed the findings from experiment 2 suggest that peripheral vision might have been utilised to guide putting action. While the Front targets might not have been optimal aiming locations to compute gap closure (Tau; Craig et al., 2000) it is likely that participants were able to compensate through the use of a visual pivot strategy, computing the relative motion of both ball and putter head from the periphery (Huttermann, Memmert, Simons, & Bock, 2013).

### **Pressure effect**

The anxiety manipulations were successful in both experiments as all groups had significantly higher level of anxiety in pressure tests compared to baseline and retention tests (Table 2.1, 2.3). It has been consistently shown in the literature that anxiety disrupts QE duration and location, leading to researchers considering QE as an objective measure of visual attentional control (Behan & Wilson, 2008; Vickers & Williams, 2007). However when trained with QE training, participants maintained effective gaze behaviour which may protect them from adverse effects of anxiety on psychomotor performance (Moore et al., 2012a; Vine et al., 2011; Vine & Wilson, 2010).

Our results support previous studies that QE training helps performer from adverse effect of anxiety. QE duration of both groups did not change between retention and pressure tests. Previous research has revealed that QE training helps increase psychological control (Wood and Wilson, 2012) and improve stress appraisals (Moore et al., 2013); the robustness of all QE trained groups in the current study (experiment 1 and 2) under the increased pressure, may



therefore be explained by such effects. However, one important thing to notice from experiment 1 is that the Short group also maintained performance even though participants were trained a shorter QE duration which is below the optimal threshold reported by previous studies (Moore et al., 2012a; Vickers, 1992; Vine et al. 2011; Vine and Wilson, 2010). These inconsistent findings are difficult to explain from an ACT perspective, although there may be benefits in attentional control terms from being taught an effective pre-shot routine with an external focus (Wilson & Richards, 2011).<sup>3</sup>

It seems that both groups may have benefitted from the QE training, which promotes a steady gaze fixation during the unfolding of movement to ensure better putter-ball contact. The current results are therefore supportive of the findings of Oudejans and colleagues (e.g., de Oliveira et al., 2008; Oudejans, van de Langenberg, & Hutter, 2002), who have previously shown that late visual information is sufficient to maintain accuracy across a variety of basketball shooting tasks. These authors suggest that it is crucial to process the latest possible (and hence most up-to date) visual information available. In the case of basketball shooting this may be because this strategy provides the most up-to-date and relevant information about the shooter's position relative to the rim, and thus, about the distance that the ball needs to travel to reach the rim. In golf putting, it is the relative position of the putter head with respect to the ball that is the important control parameter (e.g., Craig et al., 2000). A later QE appears to support this processing.

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<sup>3</sup> I further explore anxiety effects on QE and performance in Chapter 4.

In experiment 2, although the Front group was instructed to have a final fixation on the marker, these participants were not affected by anxiety. The marker might have acted as an external cue which could have lead participants to focus externally during learning to help performance and therefore maintaining accurate putt in pressure test. Singer (2002) suggested that an external fixation period serves as a means of self-regulation to enter and sustain an optimal attentional state for performing. Such a general quieting function is supported by previous research in rifle shooting that revealed significant correlations between longer QE durations and more efficient neural activity (Janelle et al., 2000). A recent QE training study in golf putting also demonstrated that QE trained participants had more efficient putting strokes and a greater quieting of cardiac and muscle activity prior to making the putt, than traditionally trained participants even though training instruction was only relevant to the gaze orientation (Moore et al., 2012a). Indeed, in experiment 2, both groups displayed significant reduction in lateral (X-axis) and back-and-forth (Z-axis) clubhead acceleration after training compared to baseline, which are the movement patterns displayed by expert golfers (See Sim & Kim, 2010), and this was robust under influence of anxiety.

Another explanation for the effect of QE training might be found from the visual routines (Ballard & Hayhoe, 2009) involved in the training regime. Although the Front group had final fixation on the marker, the visual routines were identical, right up until the final fixation, where we simply manipulated the final location via marker (experiment 2; Table 2.2). Perhaps it should not be surprising that there were no between-group putterhead kinematics differences, given that we incorporated most of the visual routine that we have previously found to be

successful in putting (e.g., Moore et al., 2012a; Vine et al., 2010, 2011). By gaining the most relevant information early in the routine, perhaps alterations to the final location become less critical.

## **2.5. Conclusions**

To conclude, these two studies attempted to investigate how the QE ‘works’ to underpin superior performance by experimentally manipulating the duration and location in two training studies. Our results replicated previous findings that QE training helps improving performance and protecting performer from adverse effect of anxiety. However, surprisingly, both QE duration and location did not have meaningful impact on performance and kinematics of putter.

## **2.6. Directions For Future Research**

The two experiments have provided partial support for the efficacy of QE training, but they have not clarified how the QE itself underpins the performance advantage revealed in earlier studies (Moore et al., 2012a). It may be that, despite considerable research support, the QE should not be reported simply as a function of its duration (experiment 1) or its location (experiment 2). It is certainly conceivable that there may be a critical time period within the QE that needs to be protected, whereas some of the duration may be superfluous to processing requirements. Furthermore, the quality of the information provided by the QE’s location may be less important than when this information is provided; the correct temporal placement of gaze may be more crucial to successful completion than precise spatial placement (Tatler et al., 2011).

A more critical and fine-tuned conceptualization of the QE may be required that truly accounts for the importance of the timing of this information processing. The third component of the QE definition does indeed consider the timing of the QE in relation to the initiation of a task specific critical movement (Vickers, 2007). However, the QE duration itself still tends to be reported as a single value – reflecting both the time spent fixating the target prior to the initiation of movement (pre-planning) and the time spent during the movement itself (online control). Currently the majority of studies investigating the QE suggest that pre-programming function is how QE works to help performance (Mann et al. 2011; Vickers, 1996). However, the work of Oudejans and colleagues suggests that it might be critical to have a steady fixation during the online control phase QE only – to ensure accurate putter-ball contact. Indeed our results from study 1 (this chapter) revealed that changing the pre-programming time via an auditory alert (Figure 2.1, cue 5) had no effect on performance. Therefore it might be beneficial to examine QE in a way that it has not been analyzed before. By providing visual information during either pre-planning or online control phases only, I will be able to experimentally manipulate the information that is used during the QE, in order to better understand how QE works to help performance.

Additionally, due to the potential issue of limited power in the training studies in this chapter, I have decided to use more experienced performers in the next study. Compared to previous QE training studies which have also used ~10 participants per group, the differences in the instructions between control and experimental groups in this chapter were much less distinct – creating the concern that the findings are simply due to lack of power (given the inherent variability in performance).

## **Chapter 3 (Study 2): An Occlusion Paradigm to Assess the Importance of the Timing of the Quiet Eye Fixation.**

*Paper accepted:* Vine, S.J., Lee, D., Walters-Symons, R. & Wilson, M.R. An occlusion paradigm to assess the importance of the timing of the quiet eye fixation. *European Journal of Sport Sciences*.

### **3.1. Introduction**

Vision is one of the most important senses and is the key source of external information that is needed to support motor action (Land, 2009). Vision is not only critical to support simple everyday tasks, such as grasping and pointing, but also in complex sporting tasks (Hesse & Deubel, 2011). In order to produce the coordinated goal-directed movements required for such tasks (Neggers & Bekkering, 2002), motor systems in the parietal lobe are provided with critical task-relevant information from visual and gaze systems in a top-down fashion (Land, 2009). Although this process is essential for everyday mundane tasks, it is of critical importance to athletes as the efficiency and control of visual attention has been suggested to underpin superior sporting performance (Vickers, 1996). Technological advancements, such as the production of lightweight eye trackers used in gaze behaviour research, has enabled researchers to establish that vision is a critical component of successful performance outcomes.

One objective measure of vision is the Quiet Eye (QE) (Vickers, 1996), which has been characterised by an optimal length of fixation on a target. Such gaze behaviour has been consistently found in a variety of different targeting tasks,

for example dart throwing (Vickers, Rodrigues & Edworthy, 2000), billiards potting (Williams, et al., 2002) and golf putting (Wilson & Pearcey, 2009). The QE is defined as the final fixation towards a relevant target or object in the visuomotor workspace, for a minimum of 100 milliseconds (ms) and within 3 degrees of visual angle (Vickers, 2007). The onset occurs prior to initiation of the movement and offset occurs when gaze deviates off the object by more than 3 degrees of visual angle for more than 100ms.

At present, the majority of research investigating the processes behind the QE has focused on the explanation that a sufficient duration of QE represents a critical period of cognitive processing prior to movement initiation that is necessary for athletes to organise and program movement parameters, such as force, velocity and direction (Vickers, 1996). For example, in basketball free throws, Vickers (1996) showed that elite free throw shooters fixate their gaze at the basket for longer duration before the initiation of the movement and this fixation terminates at the initiation of forward throwing movement. More support for a pre-programming role of QE is Mann et al.'s (2011) study of golf putting. They examined specific neural mechanisms that might help elucidate proficiency-based differences in QE durations in a golf putting task. Specifically, they found that QE duration was closely associated with the Bereitschaftspotential (BP) - a pre-motor readiness potential. The authors inferred that the QE period serves an important preparatory motor programming function and allows time for the brain to coordinate neural structures involved in movement preparation.

However, this explanation is fundamentally limited by its inability to account for

the fact that during closed-loop control tasks (exceeding 200ms in duration), like golf putting, there is enough time for on-line adjustments to take place throughout the execution of the action (Oudejans et al., 2002). Therefore the QE, which lasts from before movement initiation to just after contact in expert performers is likely to involve components of online control as well as pre-programming to control appropriate motor response. For example, Oudejans et al. (2002) found that basketball shooting percentages were just as high with only late vision available compared to full vision, whereas early performance was severely impaired when only early visual information was provided. Klostermann et al. (2013) concluded their recent paper testing the role of QE durations in throwing by suggesting, "At the moment, the facilitation of information processing, particularly with respect to an undisturbed (online) execution of the movement, seems to be a promising candidate for explaining the positive QE effect on a functional level" (p8). The current study sought to shed light on this contention and extend the knowledge derived from previous studies.

The findings from the work of Oudejans and the null effects of Chapter 2 suggest that performance variability might be more closely related to the latter component (online) of the QE, rather than early (pre-programming) components. The aim of the present study is therefore to directly manipulate this availability of visual information using an occlusion paradigm with experienced golfers. Based on Oudejans et al. (2002) we predicted that occluding late visual information would have a significant detrimental effect on putting performance compared with a control (no occlusion) condition. Moreover, we also predicted that occluding early visual information would have no significant detrimental

effect on performance compared to the control (no occlusion) condition (based on Chapter 2 experiment 1).

### **3.2. Methods**

#### **Participants**

Twenty seven golfers participated in the experiment (Mean age = 24.53, *SD* = 8.57) with an average handicap of 5.8 (*Range* = +2 to -16; *SD* = 5.01).

Participants volunteered to take part and all provided written consent. Local ethics committee approval was obtained prior to testing.

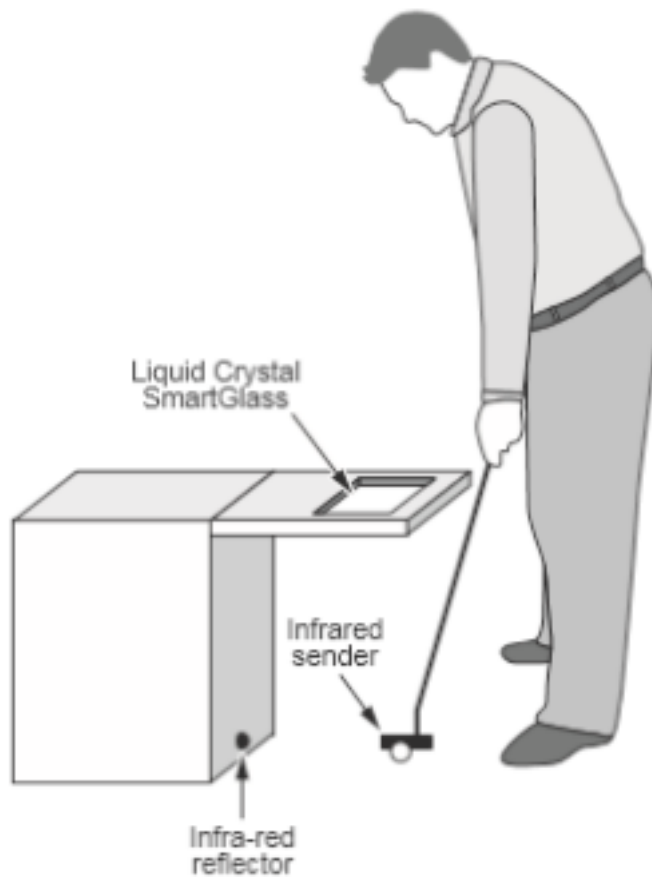
#### **Apparatus**

Putts were taken from 10 feet (3.05m), directed to a regular hole (10.80cm diameter) on an indoor artificial putting green. All participants used a standard length (90 cm) steel-shafted blade style putter (Sedona 2, Ping, Phoenix, AZ) and standard-size (4.27cm diameter) white golf balls. A Liquid Crystal (LC) SmartGlass panel (28 x 19cm) (SmartGlass International; London), mounted on a wooden box, was used to occlude the view of the ball during different phases of the putting action (see Figure 3.1). The LC SmartGlass is switched on (clear) and off (opaque) when an electrical current is passed through the glass. An infrared sender was fitted to the putter head, and an infra-red reflector was mounted on the wooden box behind the position of the ball. As the infra-red signal was broken, the screen would change states from clear to opaque or vice versa, depending on the experimental condition.



## **Design**

Participants took six putts (cf. Cooke et al., 2010; Moore, Vine, Wilson, & Freeman, 2012b) in each of three, counterbalanced, blocked occlusion conditions: no occlusion, early occlusion and late occlusion. Six putts were used as a compromise between obtaining a meaningful average, and preventing participants from learning to adjust their technique in order to overcome the visual constraints imposed by the task. For all trials participants had to look directly through the LC SmartGlass and position their putter behind the ball before initiating their own pre-shot routine (see Figure 3.1). In the no occlusion (control) condition, the screen remained clear throughout the entire preparation and execution phases of the putts. In the early vision condition, the screen was clear during the preparation phase, however, on the initiation of the backswing (when the laser signal was broken) the screen became opaque and remained opaque throughout the execution of the putt. In the late vision condition, the screen was made opaque once the putter was positioned behind the ball (i.e. during the preparation phase). On initiation of the backswing, the screen became clear, and remained clear until the putt had been executed.



*Figure 3.1. A diagram of the experimental set up showing key elements of the occlusion method: a) Infra-red reflector; b) Liquid Crystal SmartGlass; c) Infrared sender.*

## **Procedure**

On attending the single testing session, participants read an information sheet and then gave their written informed consent. Participants were first allowed twenty familiarization putts from 10 feet, before the first of the three counterbalanced conditions was explained. After familiarization putts participants completed six experimental putts, during which performance and

kinematic data were continuously recorded. After each condition participants were given a two minute rest period while the next condition was explained. This procedure was repeated for all three conditions. Finally, participants were thanked, debriefed and given the opportunity to discuss their performance with the experimenter.

## **Measures**

***QE duration.*** QE duration was defined and calculated as outlined in Chapter 2.

The calculation of the QE duration in the late condition (where the ball was occluded during the putting stroke) required a degree of estimation. Specifically, the position of the ball was recorded in relation to its distance from two of the sides (left and bottom) of the LC glass as displayed on the Eyevision software monitor. QE offset occurred if the circular cursor moved away from that position during the putt.

***Performance.*** Mean radial error (the average distance the ball finished from the hole in cm) was recorded as measure of putting performance, as in Chapter 2 (using a Logitech Web Cam mounted on a tripod above the hole).

***Putting kinematics.*** Acceleration of the clubhead in three axes was recorded using a tri-axial accelerometer (LIS3L06AL, ST Microelectronics, Geneva, Switzerland) as described in Chapter 2, experiment 2.

***Statistical analysis.*** Mean values from the six putts taken were computed and subjected to a series of repeated measures one-way Analysis of Variance (ANOVA). If sphericity assumptions were violated the Greenhouse-Geisser

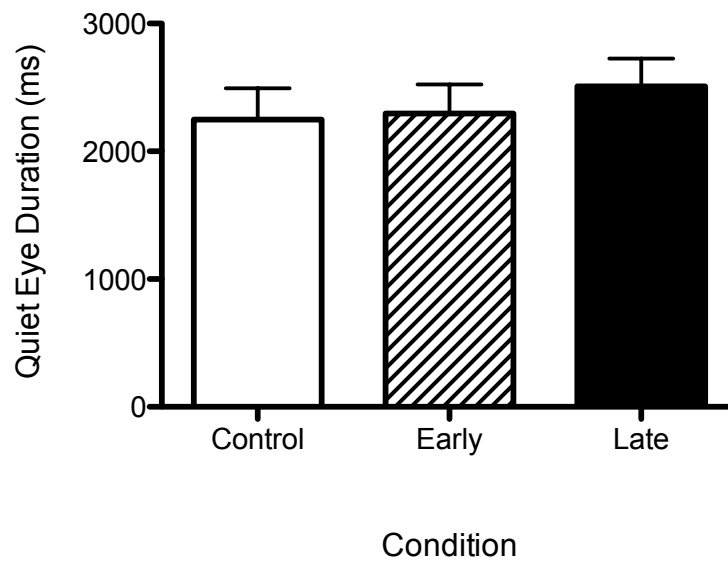
corrections were applied. Significant differences were followed up with Least Significant Difference (LSD) corrected pair-wise comparisons. Effect size was calculated using partial eta squared ( $\eta_p^2$ ) for omnibus comparisons.

### **3.3. Results**

A second analyst blindly scored 10% of the codeable trials (1 from each participant) and inter-rater reliability was assessed using the interobserver agreement method (Thomas & Nelson, 2001). This analysis revealed a satisfactory level of agreement at 96.6% (Moore et al., 2012a).

#### **QE duration**

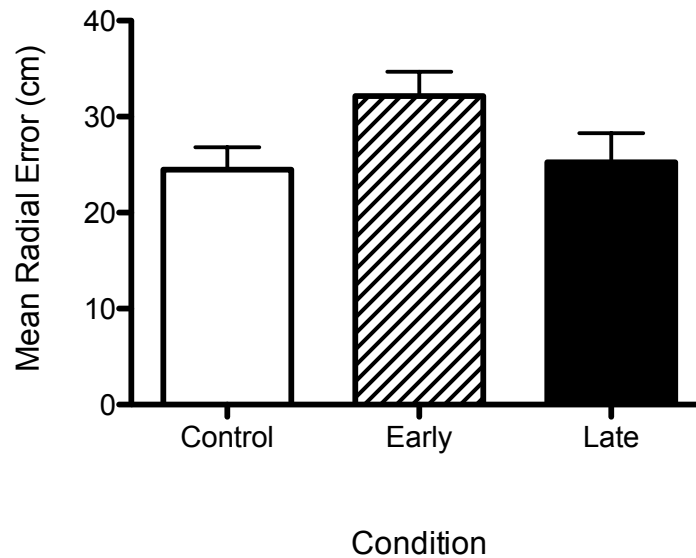
ANOVA revealed no significant main effect for condition,  $F(2,36) = .725$ ,  $p = .491$ . QE duration was similar in all conditions. QE duration data are presented in Figure 3.2A.



*Figure 3.2A. Mean (SE) QE duration (ms) for control, early vision and late vision conditions.*

### **Performance**

ANOVA yielded a significant main effect for condition,  $F(2,52) = 4.22$ ,  $p = .020$ ,  $\eta_p^2 = .14$ . Pairwise comparisons revealed that mean radial error for control ( $24.47 \pm 12.14\text{cm}$ ) and late vision ( $25.26 \pm 15.63$ ) conditions were significantly smaller than the early vision ( $32.14 \pm 13.17\text{cm}$ ) condition ( $ps = .020$  and  $.039$  respectively). Performance data are presented in Figure 3.2B.



*Figure 3.2B. Mean (SE) radial error (cm) for control, early vision and late vision conditions.*

### **Putting kinematics**

Kinematic analyses revealed significant condition main effects only for X-axis acceleration,  $F(2,48) = 4.56$ ,  $p = .015$ ,  $\eta_p^2 = .16$ ; and Y-axis acceleration,  $F(2,48) = 3.44$ ,  $p = .040$ ,  $\eta_p^2 = .13$ . There was no significant condition main effect for Z-axis acceleration,  $F(2,48) = 2.00$ ,  $p = .146$ . Pairwise comparisons revealed that X-axis acceleration for the early vision condition was reduced in comparison to both the late vision and control conditions ( $ps = .004$  and  $.026$  respectively). Y-axis acceleration for the early vision condition was greater than the control condition ( $p = .013$ ), but there were no differences between the late vision and both the early and control conditions ( $ps = .442$  and  $.101$  respectively). The full kinematic variable results are presented in Table 3.1.

*Table 3.1. Mean (SD) putter kinematic variables for control, early vision and late vision conditions.*

	Control	Early	Late
X-axis acceleration (m.s <sup>-2</sup> )	0.51 (0.22)	0.41 (0.21)	0.52 (0.24)
Y-axis acceleration (m.s <sup>-2</sup> )	1.04 (0.20)	1.09 (0.18)	1.06 (1.78)
Z-axis acceleration (m.s <sup>-2</sup> )	4.07 (1.17)	3.96 (1.08)	3.90 (1.22)

### **3.4. Discussion**

The aim of this study was to directly manipulate the availability of visual information during the QE period using an occlusion paradigm with experienced golfers, so to improve our understanding of the importance of the timing of the QE. Experienced golfers were asked to perform putts in three different conditions that manipulated the visual information available. Based on the findings of Oudejans et al. (2002) and our own null findings in Chapter 2, we predicted that occluding late visual information (online control) would be more disruptive to performance than occluding early (pre-planning) vision. As predicted, we found a detrimental effect on performance when late vision was occluded while no detrimental effect was found when early vision was occluded; the mean radial error for clear condition was smallest at 24.47 cm while mean radial error for early and late conditions were 32.14 cm and 25.26 cm respectively. These findings corroborate those of Oudejans et al. (2002) who have provided previous support for the importance of the use of late visual information during the basketball jump shot.

While in previous occlusion research it was not possible to capture eye tracking data (Oudejans et al., 2002; De Oliveira et al., 2006), we were able to do so in the current study. This is an important addition to the body of literature and a manipulation check that has not been possible in previous studies (see Oudejans et al., 2002). Interestingly, there were no differences in QE across the conditions that can explain this performance effect (Figure 2a). Indeed, across all three occlusion conditions the performers displayed QE durations similar to those demonstrated by other experienced performers in normal putting from this same distance (e.g., Vine et al., 2011). When visual information was occluded participants used a strategy of keeping their eye steady in the location that the ball had previously been.

Taking into consideration the QE findings there are two possible explanations for the differences in performance across the conditions. The first is that early visual information is not needed to plan and execute the movement, and so occluding such information had no effect on performance; however this seems unlikely given the strength of the evidence to support the early and long programming of movements that is supported by the QE (Vickers, 1996; Williams et al., 2002). An alternative explanation is that, the proportion of the QE period that occurs before movement, simply serves the purpose of helping the performer to focus their attention. The steady eye may reflect the focused attention needed to internally programme the movement, but visual information was not being extracted from the scene. Interestingly, in the early vision condition when late visual information was occluded, performance suffered despite the eye remaining steady. This provides support for a visual processing (online control) function for the proportion of the QE that occurs during the



movement. Here visual information is being actively extracted and processed so to aid the control of the putter head and to ensure good putter-ball contact (Craig et al., 2000). The visual processing of the target (ball) is preferred as late as possible with reference to the end of the movement (contact between putter and ball; Oudejans et al., 2002).

While there were no interesting findings for the Y and Z axis acceleration data, the X-axis acceleration may provide an explanation for the combined differences in both performance and QE between the conditions. The average x-axis acceleration was increased for both the control and the late vision conditions, in comparison to the early vision condition. We suggest that the increased X-axis acceleration in the control and late vision conditions reflects the use of the late visual information to control the movement online, causing variations in the position of the club head. Adjustment to the position of the putter head during the back and fore swing, helped to ensure that the putter face was square at contact (Pelz, 2000) and that there was a good contact between ball and putter, explaining why performance was improved in these conditions (see Karlsen et al., 2008). In the early vision condition, the late visual information was removed, and so the performers did not have the ability to adjust on-line the movement, resulting in reduced acceleration. While increased variability in putter head kinematics has been associated with poorer performance (see Bartlett, Wheat & Robins, 2007) research also suggests that some 'functional variability' is a characteristic of expert and accurate performance. Functional variability allows for the emergence of a movement which is tailored towards the end goal (striking the ball), and without this variability performers could not adapt to incorrect positioning at any stage of the

action (Langdown, Bridge & Li, 2012). For example, Sim & Kim (2010) showed that the directional variability of the putter head during the swing increases with the length of the putt, and this increase in variability is greater for expert (more accurate) golfers, compared to novices.

While the results support our hypotheses, there are caveats to our interpretation of an important role of late visual information in guiding putter-ball contact. First, it is perhaps not too surprising that performance was impaired in the early vision condition, as vision was not available to help guide online control for the entire putting stroke. Anecdotal evidence from participants raised the issue of reinvestment (Masters & Maxwell, 2008) or explicit monitoring (Beilock & Carr, 2001) in the early vision condition. With vision removed, a number of participants reported that they were more aware of the way in which they were controlling the putter to make the stroke, as this kinesthetic information was all that was available. As experienced performers, any contingency that raises awareness of the mechanics of the stroke is likely to be detrimental to performance (Beilock & Gray, 2012). Unfortunately, we were unable to explore these mechanisms further, as our kinematic data were equivocal in reflecting conscious control (Poolton, Maxwell, Masters, & Raab, 2006).

Second, not only did the late information condition provide participants with vision of the entire putting stroke, but the visual routine leading up to their final (occluded) gaze on the ball may have provided them with all the pre-programming information they needed to plan the putt, despite not seeing the ball prior to the initiation of the putting stroke. There is also some evidence that the backswing of the putter might still be considered as pre-programming and

that only the downswing should be considered as being truly online control (Craig et al., 2000). Future research should seek to extend the current study by including two additional conditions that would allow vision to be manipulated at the end of the backswing, as well as the start of the backswing. Providing vision in either the backswing or the downswing of the putting stroke would enable the relative role of the QE in assisting with pre-programming and online control of visually guided movement to be further explored. It is a limitation of the current study that we were unable to explore these issues due to the limited degree of software control we had with the liquid crystal display.

### **3.5. Conclusions**

The aim of current study was to directly manipulate the availability of visual information during the QE period using an occlusion paradigm with experienced golfers. Our results supported the findings of Oudejan et al. (2002) that QE provides online control function to help performance. The late proportion of the QE that occurs during the movement may reflect online control of the movement. This phase of the action requires visual guidance, and so visual feedback is used to adjust and control movement online. Gaze may be stabilised for longer than this critical period in order to internally process movement, or as part of a pre-performance routine, but, a growing body of evidence (e.g., Klostermann et al., 2013; Oudejans et al., 2002), points to a critical role for late processing of visual information. Future studies should seek to further elucidate the relative roles of pre-programming and online control in explaining the QE-visuomotor performance relationship, and also examine the individual proportions of the QE (before and after initiation of movement) that may account for performance variability

### **3.6. Directions For Future Research**

In Chapter 3, we have experimentally manipulated the timing of QE to explore which component of QE might support golf putting performance. It was shown that disruption in visual information during latter portion of QE adversely affected putting accuracy. The results suggest that an online control role of QE provides most of the performance advantage of QE – late information was more important than early information. These results also speak to findings from research that has shown that when anxiety disrupts QE duration – shortening of QE duration is due to early QE offset. The following chapter therefore seeks to extend the findings of Chapter 3 and adopt an anxiety manipulation to see if similar results are found as in the mechanical manipulation used in the current chapter. A caveat of those researches examining effect of anxiety on QE is that we do not know how early QE offset occurs, i.e does it happen before the initiation of movement (during pre-programming) or after the initiation of movement (during online control)? Furthermore, all studies that have examined how anxiety affects QE duration and performance have adopted blocks of multiple trials that might dilute the true effect of anxiety. Currently no studies have examined QE at the specific point of performance failure. Therefore in next chapter, I will adopt a more ecologically valid method of testing how QE reacts to the heightened level of anxiety; using a putting shootout task. QE also will be divided into two components, early (pre-programming) and late (online control) to investigate which part of QE is primarily responsible for the reduction in QE duration under the influence of anxiety.

## **Chapter 4 (Study 3): Quiet Eye and Choking: Online Control Breaks Down at the Point of Performance Failure.**

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### **4.1. Introduction**

To produce accurate goal-directed movements, the motor system requires accurate and timely visual information about targets critical to task completion (Land, 2009). Models of visuomotor control suggest that the gathering of such information is under the control of top–down attention (for a review, see Land, 2009). One objective measure of visual attentional control that has been the subject of recent research attention is the quiet eye (QE; Vickers, 1992)—defined as the final fixation toward a relevant target before the initiation of a critical movement (Vickers, 1996). The finding that experts demonstrate earlier and longer QE durations (QED) than novices is one of the most robust in the perceptual-cognitive expertise literature (for a meta-analysis and review, see Mann et al., 2007).

However, even experts can “miss,” and the QE has been shown to be sensitive to such intra-individual variations in performance—with successful attempts having longer QED than unsuccessful attempts (Mann et al., 2007).

The *choke* is one particular classification of miss that has been the topic of much recent research in sport psychology (for a review, see Hil, Hanton,

Matthews, & Fleming, 2010). Choking is defined as “a critical deterioration in skill execution leading to substandard performance that is caused by an elevation in anxiety levels under perceived pressure at a time when successful outcome is normally attainable by the athlete” (Mesagno & Mullane-Grant, 2010, p. 343). Interference to optimal attentional processing has been implicated as central to the choking experience (Gucciardi, Longbottom, Jackson, & Dimmock, 2012). Several recent studies have revealed anxiety-induced disruptions in attention—as indexed by shortened QED—in a range of far aiming tasks including simulated archery (Behan & Wilson, 2008), shotgun shooting (Causer et al., 2011a), dart throwing (Nibbeling, Oudejans & Daanen, 2012), basketball free-throw shooting (Vine & Wilson, 2010; Wilson et al., 2007), golf putting (Moore et al., 2012a, Vine, Moore, & Wilson, 2012, Vine et al., 2011), and soccer penalty shooting (Wilson, et al., 2009b).

These studies discussed the impairment of optimal attentional control (QE) in relation to the predictions of attentional control theory (ACT; Eysenck, Derakshan, Santos, & Calvo, 2007). Specifically, ACT suggests that anxiety causes an increase in the sensitivity and influence of the stimulus-driven (bottom–up) attentional system at the expense of the goal-directed (top–down) attentional system. According to ACT, anxiety impairs processing efficiency by reducing attentional control and by making it difficult for the goal-directed attentional system to override the stimulus-driven attentional system (Eysenck et al., 2007). In far aiming tasks, this impairment due to increased anxiety has been reflected in attenuated QED (less effective goal-directed attentional control), presumably because of an inability to inhibit distracting thoughts related to the consequences of poor performance (for reviews, see Wilson,

2012 and Nieuwenhuys & Oudejans, 2012).

The current study seeks to overcome two potential limitations in research using the QE to examine the processes underpinning choking in sport. First, much of the experimental research examining choking adopts blocked pressure conditions, with mean values calculated to represent the entire pressure condition (for notable exceptions, see Wood and Wilson, 2011 and Woodman and Davis, 2008). Although such an approach ensures good internal control and measurement reliability, it is inconsistent with real-world sporting competition where pressure-induced failure is typically a one-off event. The current study therefore adopts a novel approach that allows differences in attentional control to be examined at the point of performance failure, in a pressurized task where every shot counts.

Second, in an attempt to establish why longer QED support improved motor accuracy, researchers have tended to limit themselves to a motor pre-programming explanation (Horn, Okumura, Alexander, Gardin, & Sylvester, 2012; Mann et al., 2011; Williams et al., 2002). Vickers' seminal study in basketball free throw shooting suggested that experts initiated an early QE to the target to set the parameters of the shot and then suppressed visual information during the execution phase to protect these parameters (Vickers, 1996). In effect, Vickers' early conceptualization of the QE phenomenon (the location suppression hypothesis) suggested that using online control was a less expert strategy, prone to disruption from visual distraction (Vickers, 1996). Although the location suppression element of the theory has received little attention in the literature (for an exception, see Williams et al. 2002), the

emphasis on a pre-programming role for the QE has remained. For example, Mann et al. (2011) concurrently examined the Bereitschaftspotential, a premotor readiness potential, and QE among a population of experienced golfers, as they made putts from 12 ft. Their results revealed that the QE and the Bereitschaftspotential were closely associated, supporting their contention that the QE served an important preparatory motor programming function.

Although the work of Mann et al. (2011) has several strengths, the definition of QE used in the study is contradictory to other research. Specifically, Mann et al. (2011) only considered the duration of the QE that occurs up until the initiation of movement, whereas previous research has shown that the QE of experienced golfers is steady on the ball before the stroke, throughout the stroke, and often beyond putter–ball contact (Vickers, 1992; Vickers, 2007; Wilson & Pearcey, 2009). QE-dwell, the proportion of the QE that occurs after contact with the ball, is more likely related to online control rather than motor preparation (Vickers, 2007). Vickers proposes that an overt gaze shift away from the ball at around the point of contact is preceded by a covert attentional shift that occurs approximately 100–300 ms before contact. This shift in attention is potentially disrupting and can lead to poor contact between putter and ball (Vickers, 2007; Vine et al., 2011). With evidence supporting the importance of accurate gaze control during (and after) the putt (Vickers, 1992), it is unlikely that the QE in golf putting reflects only the pre-programming of movements to be run in an open loop (predictive) fashion (cf. Oudejans et al., 2002; Panchuk & Vickers, 2009).

Indeed, a number of unrelated lines of research appear to support the



importance of online control during the performance of far aiming tasks. First, research examining kinematic profiles in golf putting suggests that the putting action is continually adjusted on the basis of visual information ( $\tau$ ) during movement execution (e.g., Coello, Delay, Nougier, and Orilaguet, 2000; Craig et al., 2000). Second, research by Oudejans et al. (2002) in basketball has suggested that performers may prefer to use late visual information to guide movement—a form of online control—rather than early predictive information. Finally, recent research by Lawrence, Khan, and Hardy (2013), has demonstrated that increased state anxiety disrupts online—as opposed to offline—control processes responsible for the visual regulation of limb movements in target-directed aiming. Such impairments in online control resulted in subsequent decrements in task performance (Lawrence et al., 2013).

The aim of the current study was therefore to (1) examine if reductions in the QED of expert golfers might explain misses in a “shootout” golf putting task under incentives for good performance. We predicted that QED would be significantly reduced on the final (missed) putt compared with the penultimate (the last successful attempt before the miss) and first (successful) putts in the task, irrespective of how many putts were taken. (2) We also explored the extent to which pressure might influence either the early (pre-programming) or late (online control and dwell) components of the QED. We predicted that the reduction in the overall QE for the final (missed) putt will be due primarily to a reduction in the proportion that occurred after movement had been initiated (online control), thus suggesting that choking is related to inferior attentional control during the latter phases of the putting stroke.

## **4.2. Methods**

### **Participants**

Fifty right-handed expert golfers (mean age = 29.34 yr, SD = 14.00) with single figure handicaps, average handicap of 3.6 (range = +2 to 9; SD = 2.81), volunteered to participate in the study. Written information about the study was provided and written consent was gained from all participants. Local ethics committee approval was obtained before the start of testing.

### **Apparatus**

Participants putted from 5 ft (1.52 m) to a regulation hole (10.80 cm diameter) on an artificial putting green, using standard size (4.27 cm diameter) white golf balls and their own putter. An Applied Science Laboratories (ASL, Bedford, MA) Mobile Eye Tracker incorporated with a laptop (Lenovo R500 ThinkPad) installed with Eyevision (ASL) recording software was used to measure and record momentary gaze (at 30 Hz). A circular cursor (representing 1° of visual angle) indicating the location of gaze in a video image of the scene (spatial accuracy of  $\pm 0.5^\circ$  visual angle; 0.1° precision) was recorded for offline analysis. The laptop and recording devices were placed on a desk behind the participant to minimize distraction.

### **Measures**

**Anxiety.** Cognitive state anxiety was measured at three time points (baseline, before shootout, and after shootout) using the Mental Readiness Form 3 (MRF-3; Krane, 1994; as in Chapter 2).

***Movement phase durations.*** The durations of the phases of the putting action (preparation, backswing, and foreswing) were calculated using Quiet Eye Solutions software (Quiet Eye Solutions Inc., Calgary, CA). The preparation phase represented the time from the placement of the putter behind the ball, until the initiation of the backswing. The backswing phase began with the first backward movement of the clubhead and finished as the clubhead changed direction at the top of the backswing. The foreswing phase began with the first forward movement of the clubhead and finished when the clubhead contacted the ball (Vickers, 2007).

***QE duration.*** The QE was operationally defined in a slightly different manner to Chapter 2 and 3 in order to test our specific hypotheses. Rather than onset and offset, we defined the QE in terms of the proportion that occurs before (pre-programming), during (online control), and after (dwell) the initiation of the critical movement (the start of the backswing).

***Pre-programming duration (QE-pre).*** The pre-programming phase of the QE was defined as the component of the QE starting at QE onset and ending with the initiation of the backswing. As such, this duration reflects the proportion of the QE that may be responsible for the pre-programming of the ensuing putting stroke.

***Online control duration (QE-online).*** The online control phase of the QE was defined as the component of the QE starting with the initiation of the backswing

and finishing when the putter contacted the ball, or when gaze deviated from the ball by 1° of visual angle for more than three frames. As such, this duration reflects the proportion of the QE that may be largely responsible for the online control of the putting stroke.

***Dwell duration (QE-dwell).*** The dwell phase of the QE was defined as the component of the QE that started when the putter contacted the ball and ended when the gaze deviated from the same location on the green by 1° of visual angle for more than three frames (Vickers, 2007). If the QE offset occurred before ball–putter contact, then dwell was recorded as zero.

## **Procedure**

Participants attended individually and after reading an information sheet provided written informed consent. An ASL mobile eye tracker was fitted on the participant and calibrated using five golf balls positioned at their feet.

Participants were asked to adopt a stance as though they were about to putt and instructed to hold their gaze steady on the center of each of the five balls in turn. Participants were given the chance to warm up and familiarize themselves with the putting green by taking a series of 20 putts from a distance of 10 ft.

After these putts, a baseline measure of anxiety was collected using the MRF-3.

Participants were then asked to take part in a shootout putting task, which involved holing as many balls as possible from 5 ft without missing. This is a popular task used by golfers to practice their short putting under pressure (Pelz, 2000); it emphasizes the importance of every single putt and is therefore a useful task for examining processes underpinning performance failure. The number of consecutive successful putts achieved by the participants ranged

from 3 to 237 (mean = 23.06, SD = 35.04). If participants missed the first or second putt, they were given the opportunity to take part again (after a short break), although this only happened on three occasions.

To incentivize the participants and increase the levels of pressure experienced, a £50 cash prize was made available to the person who made the most consecutive putts. Furthermore, participants received ego-threatening feedback about their 20 practice putts. An experimenter informed them that their performance on the 20 practice putts would put them in the bottom 30% of participants that had already taken part (Vine et al., 2011). Finally, participants were told that their scores would be shared with all participants who had taken part in the study via a published leader board (Vine et al., 2011). Participants subsequently completed the MRF-3 before beginning their shootout putts. Once a putt was missed, participants filled out the MRF-3 for a third time. MRF-3 scores taken at the beginning and end of the shootout were averaged to give an aggregate level of anxiety experienced throughout the shootout, which was later compared with their baseline measure given after the familiarization putts. Finally, participants were thanked, debriefed, and offered the opportunity to discuss their gaze and performance data with the experimenter.

## **Data Analysis**

The various QE and movement phase durations were calculated for the first, penultimate, and final (missed) putts and subjected to one-way repeated-measures ANOVA. Greenhouse–Geisser corrections were applied if sphericity assumptions were violated. Significant differences were followed up with Bonferroni-corrected pairwise comparisons. A paired samples *t*-test was

performed on the self-report anxiety data (baseline vs average during shootout). Effect sizes were calculated using partial eta squared ( $\eta_p^2$ ) for omnibus comparisons and Cohen  $d$  for simple comparisons.

### **4.3. RESULTS**

#### **Cognitive anxiety**

A paired samples  $t$ -test revealed that participants reported significantly higher cognitive anxiety,  $t(49) = 9.91$ ,  $p < 0.001$ ,  $d = 1.63$ , during the shootout (mean = 5.5, SD = 2.65) compared with the baseline (mean = 2.13, SD = 1.49) condition.

#### **Movement phase durations**

ANOVA revealed a significant main effect for preparation phase duration,  $F(2,98) = 5.12$ ,  $p = 0.008$ ,  $\eta_p^2 = 0.10$ . *Post hoc* comparisons revealed that preparation was significantly longer for first putts compared with penultimate putts ( $p = 0.015$ ). There were no significant differences between final putts and both first ( $p = 0.352$ ) and penultimate ( $p = 0.143$ ) putts. There were no significant differences in backswing phase duration  $F(2,98) = 2.70$ ,  $p = 0.072$ ,  $\eta_p^2 = 0.05$ ) and foreswing phase duration,  $F(2,98) = 1.94$ ,  $p = 0.150$   $\eta_p^2 = 0.04$ , across the three putts. Movement phase data are presented in Table 4.1.

*Table 4.1. Mean  $\pm$  SD duration (ms) of the preparation, backswing, and foreswing phases of the first, penultimate, and final putts of the shootout task.*

	First	Penultimate	Final
<b>Preparation phase</b>	2401.57 $\pm$ 1589.67	1836.08 $\pm$ 1080.62	2059.52 $\pm$ 1183.97
<b>Backswing phase</b>	556.32 $\pm$ 159.33	511.68 $\pm$ 148.65	530.98 $\pm$ 119.34
<b>Foreswing phase</b>	339.02 $\pm$ 71.98	328.06 $\pm$ 70.90	315.06 $\pm$ 70.05

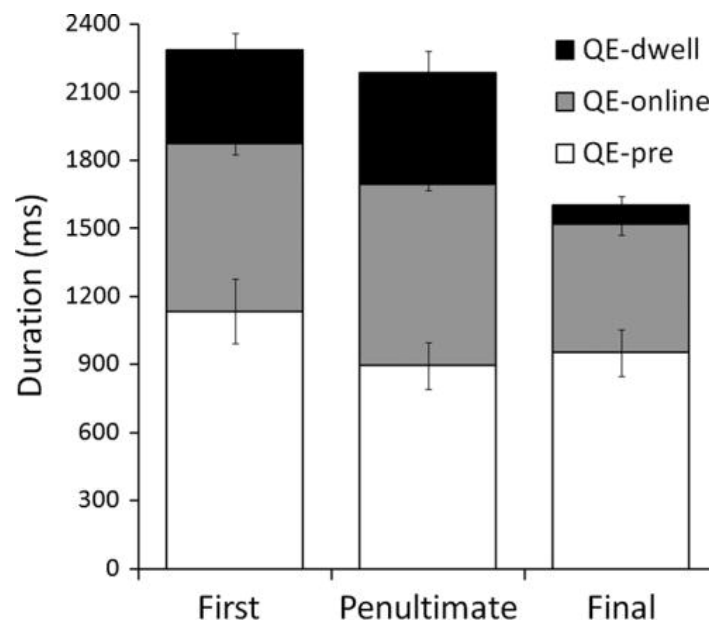
### **QE durations**

ANOVA yielded a significant main effect for overall QED,  $F(2,98) = 14.71$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.23$ ). *Post hoc* comparisons revealed that the total QED was significantly shorter for final putts when compared with first and penultimate putts ( $p$ 's  $< 0.001$ ). There was no significant difference in QED between first and penultimate putts ( $p = 0.477$ ).

There were no significant differences in QE-pre across the three putts,  $F(2,98) = 1.12$ ,  $p = 0.330$ ). Participants took similar lengths of time ( $\sim 1000$  ms) between fixating the ball and initiating their putting strokes on first, penultimate, and final putts.

However, there was a significant main effect for QE-online  $F(2,98) = 10.33$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.17$ ). *Post hoc* comparisons revealed that the component of the QE occurring during the putting stroke was significantly shorter for final putts compared with first ( $p = 0.008$ ) and penultimate putts ( $p < 0.001$ ). There was no significant difference in QE-online between first and penultimate putts ( $p = 0.274$ ).

Finally, there was a significant main effect for QE-dwell  $F(2,98) = 12.65$ ,  $p < 0.001$ ,  $\eta^2_p = 0.21$ ). *Post hoc* comparisons revealed that the duration of a stable fixation on the ball location after contact was significantly shorter for final putts when compared with first and penultimate putts ( $p$ 's  $< 0.001$ ). There was no significant difference in QE-dwell between first and penultimate putts ( $p = 0.405$ ). QE data are presented in Figure 4.



*Figure 4. Mean  $\pm$  SEM duration of the pre-programming (QE-pre), online control (QE-online), and dwell (QE-dwell) components of the overall QE duration (QED; sum of the three subphases) for the first, penultimate, and final putts of the shootout.*

#### **4.4. DISCUSSION**

The QE has been shown to underpin the accurate performance of visuomotor skills in a number of different sports (for a review, see Wilson et al., 2015).

Studies indicating that the QE is susceptible to disruption under conditions of



heightened anxiety caused by performance pressure have examined changes in mean values, derived from blocks of multiple trials (for a review, see Vine et al., 2014). Such an approach may not only dilute the effects of pressure but also fail to consider the individual “variability” in QED that may occur when a shot is missed. As such, the first aim of this study was to adopt a novel approach that allowed changes in QED to be examined at the precise point of performance failure, in a pressurized task where every shot counted (a “shootout”). Fifty expert golfers with single figure handicaps were recruited to take part, reflecting a larger and more elite sample than has been previously adopted in research examining the QE in golf putting (Mann et al., 2011; Vickers, 1992; Wilson & Pearcey, 2009).

### **QE duration**

To ensure that participants were incentivized and that the conditions of the shootout task simulated those of sporting competition, a pressure manipulation was used. Participant’s responses to the MRF-3 questionnaire supported the effectiveness of the manipulation; anxiety levels were significantly higher during the shootout than at baseline. The reported anxiety levels are similar to those found in other laboratory environments (e.g., Vine & Wilson, 2010, 2011; Wilson et al., 2009a); however, we acknowledge that they are unlikely to be as high as those encountered in real competition. Furthermore, as mobile eye trackers are not permitted to be worn in real competition, we believe that the novel approach and pressure manipulation used in the present study may represent a best attempt at understanding failure at the exact point of pressure.

For the successful first and penultimate putts, QED values were 2284 and 2205

ms, respectively (Fig. 4.1). These durations are of similar magnitude to previous research examining successful putts for expert golfers (Vickers, 1992; Vine et al., 2011, Wilson & Pearcey, 2009). However, the final (missed) putt was accompanied by a QE (1601 ms) that was significantly shorter than both the first and the penultimate putts (Fig. 4.1). This duration is below the optimal threshold of 2 s proposed for successful golf putting performance, hence, it is unsurprising that this duration was associated with unsuccessful performance (Vickers, 1992; Vine et al., 2012; Wilson & Pearcey, 2009).

Although this finding supports previous research that has shown that the average QE across a block of multiple pressure shots is attenuated (e.g., Behan & Wilson, 2008; Causer et al., 2011a; Wilson et al., 2009a), this is the first study to highlight a reduction in QE at the specific point of performance failure. It appears that the choke was associated with a lapse in visual attentional control (reduced QED), which may have led to poor accuracy. Interestingly, as the penultimate putt did not have a reduced duration, this lapse in visual attention is unlikely to have been due to attentional and/or postural fatigue experienced because of performing multiple putts. Moreover, the number of successful putts that each participant achieved before missing varied considerably (mean = 23, range = 3–237 putts), again suggesting that fatigue was unlikely to be the major factor. These findings support the predictions of ACT (Eysenck et al., 2007) and likely reflect the impairment of attentional control in terms of the mechanisms highlighted by Eysenck et al. (2007). Anxiety, resulting from competitive pressure, increased the influence of the stimulus-driven attentional system, at the expense of the goal-directed attentional system, leading to a shortening of the QE (Causer et al., 2011b;

Nibbeling et al., 2012; Wilson et al., 2009a).

### **Pre-programming versus online control**

One of the limitations of previous research examining how longer QED benefit accuracy is the focus on only a cognitive pre-programming explanation (Lawrence et al., 2013). Vickers (1992) originally identified that the duration of the fixation made during the putting action differentiated high and low handicap golfers. This finding suggests that the QE in golf putting likely serves an online control function as well as a pre-programming function. The second aim of this study was therefore to divide the QE into early (pre-programming) and late (online control and dwell) components, to determine which might be most critical to accuracy and most susceptible to breakdown under pressure.

Although there were no changes in the proportion of the QE responsible for the pre-programming of movement (QE-pre; ~1000 ms) across all three putts, there were significant reductions in measures related to online control (QE-online and QE-dwell) for the final (missed) putt (Fig. 4.1). QE-online dropped from more than 800 to 560 ms in the final putt and QE-dwell dropped from approximately 400 ms to less than 100 ms. The act of planning an eye movement to a new location has been shown to be coupled with an obligatory shift of covert attention to that location before the eyes have even begun to move (Gucciardi et al., 2012; Henderson, 2003). As such, participants' attention had likely moved from the ball before contact was made, disrupting the contact between the putter and ball (Vine & Wilson, 2010).

Importantly, these changes in QE-online and QE-dwell could not be explained by changes in the durations of the movement phases of the putt (Table 4.1).

Indeed, the only significant difference in movement was that preparation time was longer for the first putt than both the penultimate and final putts. This is perhaps not surprising and may reflect a process of getting comfortable over the first putt in the shootout. It may also reflect additional, generic parameter setting for the task which is not required once the task becomes more practiced and well learned. It is noticeable that these preparation differences are most likely due to physical adjustments because there were no differences in pre-programming QED (QE-pre; Fig. 4.1).

The results therefore support our first hypothesis that maintaining a long QE duration is critical for performing an aiming task under pressure. These findings are consistent with previous research that has demonstrated that choking under pressure is related to shorter QE durations (Wilson, 2012). Our second hypothesis was also supported, as increased anxiety impaired online control rather than pre-programming—the missed putt had a shorter QE duration than the other putts because it was attenuated rather than having started later. The findings support models of motor control that point to the importance of online visual information for regulating control of movements (e.g., Craig et al., 2000; Oudejans et al., 2002), the predictions of ACT (Eysenck et al., 2007), and recent evidence revealing that anxiety disrupts online, rather than offline, control of goal-directed aiming (Lawrence et al., 2013).

There are also implications for researchers using the QE as an objective measure of attentional control in far aiming tasks (under pressure). First, there has been inconsistency in the operational definition of the QE, and this might hamper attempts to further our understanding of its role in supporting superior performance. Second, the relative role of the QE in supporting preplanning

and/or online control might be task dependent and is likely to be influenced by the relative duration of the unfolding critical movement; the period over which online control may occur. Third, the role of the QE may be different in underpinning proficient performance versus performance under pressure. Although there has been consistent support for early QE *onset* differences between experts and novices (Mann et al., 2007), findings from the few studies examining the impact of increased anxiety on QE in aiming tasks have suggested that pressure disrupts the offset of the QE more than the onset (Vine et al., 2012). These somewhat conflicting findings suggest that performance degradation due to increased anxiety (i.e., choking) may be due to subtly different QE mechanisms than differences in performance proficiency. Novices may not initiate their QE fixation early enough to successfully pre-program the movement response to the same degree as an expert, but trained performers who choke fail to maintain their QE fixation and hence disrupt subsequent online control.

From an applied perspective, the findings further support the efficacy of QE training regimes aimed at facilitating better performance under pressure for expert performers (e.g., Causer et al., 2011b; Vine et al., 2011). Such interventions should focus on an early QE onset to optimize performance improvements (Causer et al., 2011b) and focus on maintaining the QE throughout the movement phase as a way of protecting elite performers from the negative influence of anxiety on attentional control (Vine et al., 2011).

Although the results from the current study are novel and potentially interesting, they should be considered with caution because of the limitations inherent in

the research design. First, anxiety and performance were not measured to the same level of sensitivity as the QE measures. Anxiety was not measured for every putt, which would have been possible had objective or continuous measures of arousal (e.g., heart rate) been taken, and we did not take a measure of performance error (the distance the ball finished from the hole in cm) on the final (missed) putt. Second, the present study did not assess movement kinematics of the putting stroke, and we were therefore unable to examine measures of movement variability during early and late phases of the putt, which might have provided more information on the degree to which online and offline control was impaired (Lawrence et al., 2013).

Third, an important consideration for research examining the visual attention (gaze) of participants is the degree to which visual overt attention is representative of covert attention. Recent neuroscience research suggests that a shift in gaze invariably predicts a shift in attention (Corbetta, 1998) and that it is difficult to shift the point of gaze without shifting attention (Henderson, 2003; Henderson & Hollingworth, 1999). However, it is possible that covert attention could shift (e.g., inwardly) while overt attention, as measured by QE, remains fixed. Future research should consider adopting direct cortical measures of attentional control to assess potential dissociations in the orientation of overt and covert attention (Vine et al., 2014).

#### **4.5. Conclusion**

To conclude, the results demonstrate that a disruption in visual attentional control (reduced QE duration) occurs at the precise point of performance failure

during a pressurized golf putting task. In separately assessing differences in the proportion of the QE that occurs before, during, and after the execution of the skill, the findings of the current study support Vickers' seminal work in golf putting (Vickers, 1992) but perhaps call into question the importance of a pre-programming role for the QE. Specifically, the results demonstrate that pressure has a greater impact on visual attention during the execution of the movement than it does during the preparation of this movement. The results highlight the need for future research to consider the task-specific nature of the role of QE in supporting the pre-programming and online control of goal-directed movement under stressful conditions.

## **Chapter 5. General Discussion**

The aim of this series of studies was to explore the structure of Quiet Eye, one of the three key indices of perceptual-cognitive expertise (Mann et al., 2007), in golf putting. In Study 1 (Chapter 2), two experiments were conducted to examine the influence of manipulating the main definitional components of QE, namely its *duration* and *location*. Study 2 (Chapter 3) directly manipulated availability of visual information during the QE period and was aimed at investigating the importance of the *timing* of the QE. Study 3 (Chapter 4) then applied pressure to examine how QE changes under the influence of anxiety at the time of performance failure. These studies have made incremental, though significant contributions to the body of QE literature. These contributions include (1) corroborating the efficacy of QE training in golf putting; (2) providing a greater understanding of *how* QE training might exert its positive effect on performance in golf putting; (3) providing evidence to support an online control role of QE in helping performance (in golf putting); (4) providing evidence to support predictions of ACT in golf putting. The proceeding sections offer a discussion of how this thesis' findings contribute to the literature base.

### **5.1. Summary and implications**

#### **5.1.1. QE training**

QE training has been proposed to facilitate optimal attentional control, which expedites learning and enhances performance under pressurized



circumstances (Vine & Wilson, 2010; Vine et al., 2011, Moore et al., 2012a). The results from Study 1 (Chapter 2) support findings from previous research highlighting the efficacy of QE training (Causer et al., 2011b; Harle & Vickers, 2001; Vine & Wilson 2010, 2011; Vine et al., 2011; Wood & Wilson, 2011). The unexpected, but interesting primary finding is that the benefits of QE training were evident regardless of the specific instructions in the QE training paradigm. Previous QE training studies on golf putting have used verbal and video-*feedback* and *feedforward* training paradigms (Vine & Wilson, 2010; Vine et al., 2011, Moore et al., 2012a), which revealed a positive effect on both QE duration and performance. However, in experiment 1 of Chapter 2, a modified training regime was adopted.

Specifically, audio recording was utilised to train participants and this was found to be as effective as traditional video-aid training (e.g., Vine & Wilson, 2010). Recent research has shown that an auditory feedback group performed better than a visual feedback group in the retention test of a wrist movement study (Ronsse et al., 2011) and that auditory feedback-based learning can improve movement regularity (van Vugt & Tullmann, 2015). A key implication of the study is that QE can be trained using audio-aid instruction. A benefit of audio-aid training is that the instructions are provided as the movement unfolds, whereas trainees using video-aid training have to re-generate the video image to maintain expert-like timing and duration during the completion of the learning putts. This may bring more cognitive loading which might consume more attentional resources leading to slower learning. Comparison of data from audio and video-aid training might elucidate which is superior in terms of learning and performance. However I am not able to compare the result of experiments in

Chapter 2 because QE duration of control group with video-aid training was not matched to the duration I manipulated in audio-aid training. Therefore future research should seek to explore differences in the medium by which QE training is provided.

When designing the two QE training experiments, it was hypothesized, based on the current literature, that there would be significant group effects. This led us to think that having a 'traditional' QE trained group as the control group would be sufficient to elucidate the importance of the duration and the location of QE against 'impaired' experimental groups. However, this was not the case and unfortunately this null finding makes further clarification of the mechanisms underpinning QE training difficult to address. An additional control group, (e.g., discovery learning without any instruction; see Wilson et al., 2011), would have allowed us to see if the null finding was just down to power (or other experimental issues), or whether the benefits of QE training do in fact exist regardless of the specific duration and location of the attentional focus being trained.

### **5.1.2. Influence of QE duration and location**

Duration is the most assessed component of the QE definition and it has been postulated that longer is better, at least up to a threshold (Behan and Wilson, 2008; Moore et al., 2012a; Vickers, 1992; Vine et al. 2011; Vine and Wilson, 2010). Previous QE studies have consistently revealed that superior performance (both inter- and intra-individual comparisons) is associated with longer QE durations (Causer et al., 2010; Vickers, 1997; Vickers & Williams, 2007; Williams et al. 2002; Wilson & Percy, 2009). Additionally, Klostermann

et al.'s (2013) recent study which manipulated QE duration in a throwing task using a projected target revealed that radial error was significantly less in the long QE duration trials, suggesting that QE serves not just as a by-product of superior performance but plays a functional role.

Therefore in Study 1 (experiment 1), we hypothesized that participants in the long QE group would reveal lower radial error in retention and pressure tests, compared to the short QE group. However, current findings did not meet our hypotheses. Perhaps the fact that our manipulation only influenced the portion of the QE duration which occurs prior to putter movement, while the duration of the QE that happens during and after putter-ball contact was kept constant across the group, might explain this null finding. Chapters 3 and 4 suggested that maintaining QE just before and through putter-ball contact is more important than having a long period before putter initiation to provide online control of putter-ball contact. This is in line with Vickers' (1992) finding that elite golfers held their QE on the ball during contact and QE remained on the putting surface for about 250ms after contact while gaze of near-elite counterparts often deviated away from the ball during the swing before the contact with the ball.

Chapter 2 (experiment 2) examined the importance of the location of QE in explaining how QE training might improve performance in golf putting. Contrary to our hypotheses, changing the location of fixation did not affect performance. This suggests that location of QE might not be the major factor in how QE training works. Rather the QE might simply provide a period of general psychomotor quiescence (Vine et al., 2014), which dampens central and

peripheral responses to enable more effective fine motor skill performance (e.g., Moore et al., 2012a; Cooke et al., 2014). Any steady fixation in the vicinity of the target might provide the conditions required for such psychomotor quiescence.

While provision of general psychomotor quiescence seems plausible, the role of peripheral vision should not be overlooked. Although not specifically related to golf putting, previous studies have shown that experts in various sports use a visual pivot strategy; holding gaze steady at a central location and using peripheral vision to pick up moving targets (e.g., Ripoll, 1987; Williams & Elliott, 1999). There are also researchers who advocate that information can be picked up by peripheral vision (e.g., Abernethy 1991; Williams & Davids, 1998) and used to guide online control of movement (e.g., Abahnini, Proteau, & Temprado, 1997; Lawrence, Khan, Buckolz, & Oldham, 2006). It is suggested that the putting action is continually adjusted on the basis of visual information ( $\tau$ ) during movement execution (Craig et al., 2000). In this regard, it is likely the participants in Study 1 were able to pick up the relative motion of both ball and putter-head from the periphery whilst having gaze fixed on the ball placed 45cm in front of actual ball<sup>4</sup>. However, I am not able to provide further evidence since the mobile eye tracker does not provide information outside of foveal vision. Future research might adopt *moving mask* paradigms (Reingold, Loschky, McConkie, & Stampe, 2003; van Diepen et al., 1998) to train the group with or without peripheral vision, or use a cone shaped device which could block peripheral information related to the target or putter head.

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<sup>4</sup> Jordan Spieth, the 2015 Masters' winner sometimes uses a strategy of fixating the hole on short putts (<5 feet), Cook, J. *Look back at it: Spieth's putting technique* [Video file]. Retrieved from <http://www.golfchannel.com/cooks-take-spieths-look-hole-putting-technique/>.

### **5.1.3. Pre-programming and online control**

The QE is the final fixation to a target that has an onset prior to the initiation of a critical movement and an offset that occurs when gaze moves off the target (Vickers, 2007). As the QE is defined with an onset prior to movement it is most frequently discussed in terms of providing a pre-programming role (e.g., Mann et al., 2011). In terms of this pre-programming perspective, Vickers (1996) suggested that longer QE duration allows an extended period of pre-programming during which the parameters of the movement such as direction and force as well as the timing and coordination of the limbs are fine-tuned. Although this postulation has been shown to be valid in many previous studies, our results suggest that this may not be the primary value of a longer QE for the particular skill of golf putting.

In experiment 2 of Chapter 1, I suggested that it might be the entire visual routine leading up to the final fixation before movement execution which serves the period of pre-programming of parameters of movement. In experiment 1, the visual routines (cf. Ballard & Hayhoe, 2009) were identical for each group, right up until the final fixation, where we simply manipulated the duration of pre-programming via an audiotape. The visual information required to plan the movement might be processed during the earlier parts of the visual routine (i.e. the saccades between fixations to the hole and the ball – see Chapter 2). By gaining the most relevant information early in the routine, perhaps alterations to the final QE duration become less critical. Therefore the current thesis provides some support for the contention that there may be too much emphasis placed on just the final (QE) fixation prior to a critical movement. Some researchers (e.g., Button, Dicks, Haines, Barker, & Davids, 2011; Dicks, Button, & Davids,

2010; Glöckner, Heinen, Johnson, & Raab, 2012) have suggested that focusing on only the QE might be overly reductionist, and that shifts of attention over time are important in supporting decision-making and visuomotor control. For example, Button et al. (2011) applied a Markov chain method to statistically model the probabilities of where a goalkeeper would direct gaze throughout a penalty taker's run-up (see also Dicks et al., 2010). Such an approach can identify subtle differences in visual behaviours that summary statistics are too insensitive to detect. Outside of sport, other models of visually guided movement (e.g., Ballard & Hayhoe, 2009; Land, 2009) also reflect the importance of visual routines where information is built up over time from a series of goal directed fixations.

So why do QE studies not tend to assess these earlier fixations that could be considered as part of the total visual routine underpinning performance? It is likely that researchers have simply accepted Vickers' original findings in putting (Vickers, 1992) and basketball (1996) that suggested that only the final fixation explained performance differences between experts and near experts. There is therefore a risk that an entire body of work on QE has been overly reliant on two dated studies, that while seminal and far-reaching in their impact, were carried out using dated equipment and with methodological flaws (particularly with respect to power). Additionally, there are experimental issues with using eye-trackers when the pupil rotates in orbit to an extent where it is not recognised by the software. In our data, we felt that we could not trust the veracity of gaze behaviours made ten feet away when the eyes rotated.

Although a pre-programming role of QE in golf putting as part of a visual routine

provides some explanation for how QE *works*, a number of studies (including Chapter 4) suggest that when performance breaks down in far aiming skills, it is likely to be due to the QE being attenuated, rather than starting late (Nibbeling et al., 2012; Vine et al, 2011, 2013); supporting more of an online control role for the QE. These findings corroborate the current thesis in that there may be some flexibility in how long you focus before initiating the movement, but if you break off the QE too early, performance will suffer. This critical difference in role cannot be determined via a simple measurement of QE duration. Instead, a more fine-grained approach is required that starts to determine the likely processing role of different components of the QE duration.

In order to explore the QE in more detail, Chapter 3 examined the timing of the QE by experimentally manipulating the availability of visual information via a specially designed box equipped with LCD glass which could be turned on and off dependent on putter movement. Results showed that putting accuracy was poorer when late vision was occluded while no significant difference was found in putting accuracy when early vision was occluded compared to full vision condition. This finding suggests that the disruption of visual information during online control of putter movement led to poorer performance. From an online control perspective, maintaining the late component of QE is likely to ensure a more consistent putter-ball contact. The findings of Study 1 provided evidence that a long preparation period, during which the ball is being fixated, may not be critical in supporting putting performance. Instead, only the disruption of visual information processing during the putter swing significantly impaired performance. Therefore Chapter 3 supports a stronger role for the QE in supporting online control over pre-programming.

Anecdotally, the most prevalent golf coaching instruction for putting might be that “eyes need to be kept on the ball” whilst “head remains still” throughout the execution of the putt (cf. Jordan Spieth). “Peeking”, a colloquial term for lifting the head and tracking the ball that has been struck before the end of putting stroke has been known as why golfers miss short putts (Harmon, 2007).

Although not researched in the laboratory, it has been suggested by world leading coaches and the players that when a golfer peeks, the head moves and this causes the left shoulder to open. When left shoulder is opened this leads putter-face and path off the ideal putting line (Harmon, 2007; Nicklaus, 2009; Sorenstam, 2009). Therefore this online control role of QE might explain why golfers miss short putts at the behavioural level; the disruption in online control adversely affects putting accuracy. Future studies could adopt biomechanical measure of body movement to examine how early offset of QE duration affects the posture of the golfer at putter-ball contact.

#### **5.1.4. Influence of anxiety on visual attention**

Previous studies have consistently shown that anxiety-induced disruptions of attentional control (QE) can lead to choking. However these studies have used blocks of multiple putts to measure changes in mean values between groups and conditions (for a review, see Vine et al., 2014) which might dilute the true effect of anxiety. Moreover, this approach also fails to consider the individual “variability” in QE duration that may occur when a shot is missed. Study 3 was the first study to assess the QE duration at the time of performance failure in comparison to other single attempts where performance was successful. To assess potential influence of pre-programming and online control functions of



QE on the golf putting, the QE was divided into two components, the early component (most likely to reflect pre-programming) and the late component (most likely to reflect online control).

A recent functional magnetic resonance imaging (fMRI) study investigating neural mechanism of choking under pressure has suggested that impaired top-down control can interfere with skilled motor performance (Lee & Grafton, 2015). This is in-line with the predictions of ACT as well as the findings of the current thesis; anxiety increases the influence of stimulus driven attentional control leading to early offset of QE which disrupts online control of putting execution. Taken together, these findings highlight that in golf putting, the entire QE duration might not be critical, but rather, there may be key moments when attentional control has to be perfectly co-aligned temporally with motor planning and / or control.

According to findings from this thesis, the later component of QE ensures a steady fixation on / near the ball during putter movement to guide accurate putter-ball contact (and / or maintain a quiet focus). This 'later is better' interpretation of the QE fits more comfortably within a perceptual-cognitive expertise framework than a 'longer is better' interpretation. The fact that experts need longer processing time than novices to achieve better performance has always been difficult to rationalize, when compared with an expert's ability to anticipate more quickly with less information than novices (e.g., Mann et al., 2007). While the current findings do not relate specifically to expertise, they do suggest that successful performance is likely to be underpinned by a steady QE fixation that is prioritized at a critical moment, rather than held longer to ensure

additional pre-programming time. This interpretation does not negate previous findings that have shown that experts had longer QE durations than novices, but it does call into question which part was critical and where the specific differences in QE were; early (before the movement) or late (as the movement unfolds).

Experts may still have longer QE durations than novices just by keeping a steady fixation throughout the movement, whereas novices will attenuate their QE if their gaze is flitting around in a less efficient and effective manner (see Wilson et al., 2009a). A more fine-grained analysis of the components of the QE duration might also help us to better explain the tension between, on the one hand, relating longer QE durations to better performance, while on the other, relating longer QE durations to more difficult tasks requiring longer processing (Klostermann et al., 2013; Williams et al., 2002). More difficult tasks are likely to have poorer performance so it is difficult to determine the role of lengthy QE durations in the circumstance where performance is poor in a difficult task. However, the findings of the current thesis would suggest that better performance is generally due to the maintenance of a late QE, whereas increased difficulty is more likely to elicit extended pre-programming, as movement solutions are determined (e.g., Klostermann et al., 2013). Future research should therefore seek to adopt this fine-grained approach to the QE in order to further our understanding of how the QE 'works' to support performance.

### **5.1.5. Theoretical and practical implications.**

From a theoretical perspective, the interpretation that the QE has an important role in online control of movement, supports the multiple-process model of limb control (Elliott et al., 2010), which is evolved from the two-component goal-directed aiming model (Woodworth, 1899). While this model has been tested mainly on goal-directed near aiming tasks, it may have applicability to goal-directed far aiming tasks. Golf putting requires precise control of the putter-head along a correct path to contact the ball with a suitable putter face angle in order to roll the ball on the path that leads to the hole (Karlsen, Smith and Nilsson, 2008). Furthermore golf putting also requires the right amount of force to be applied at putter-ball contact in order to reach the hole with ideal speed (Sim & Kim, 2010). Therefore this model could be supported by how online control function of QE works to help performance in golf putting.

Elliott et al.'s (2010) model suggests that there are two distinct phases in goal-directed reaching and aiming: an impulse control (pre-programmed) phase which bring limbs to the vicinity of the target, i.e. distance control, and a homing (limb-target control) phase which deals with error correction, i.e. directional control. In this sense, the backswing of the putt could be regarded as involving impulse control due to its role in distance control (Grealy & Mathers, 2014), whereas the forward swing of the putt could involve homing the putter face to the ball along the correct path.

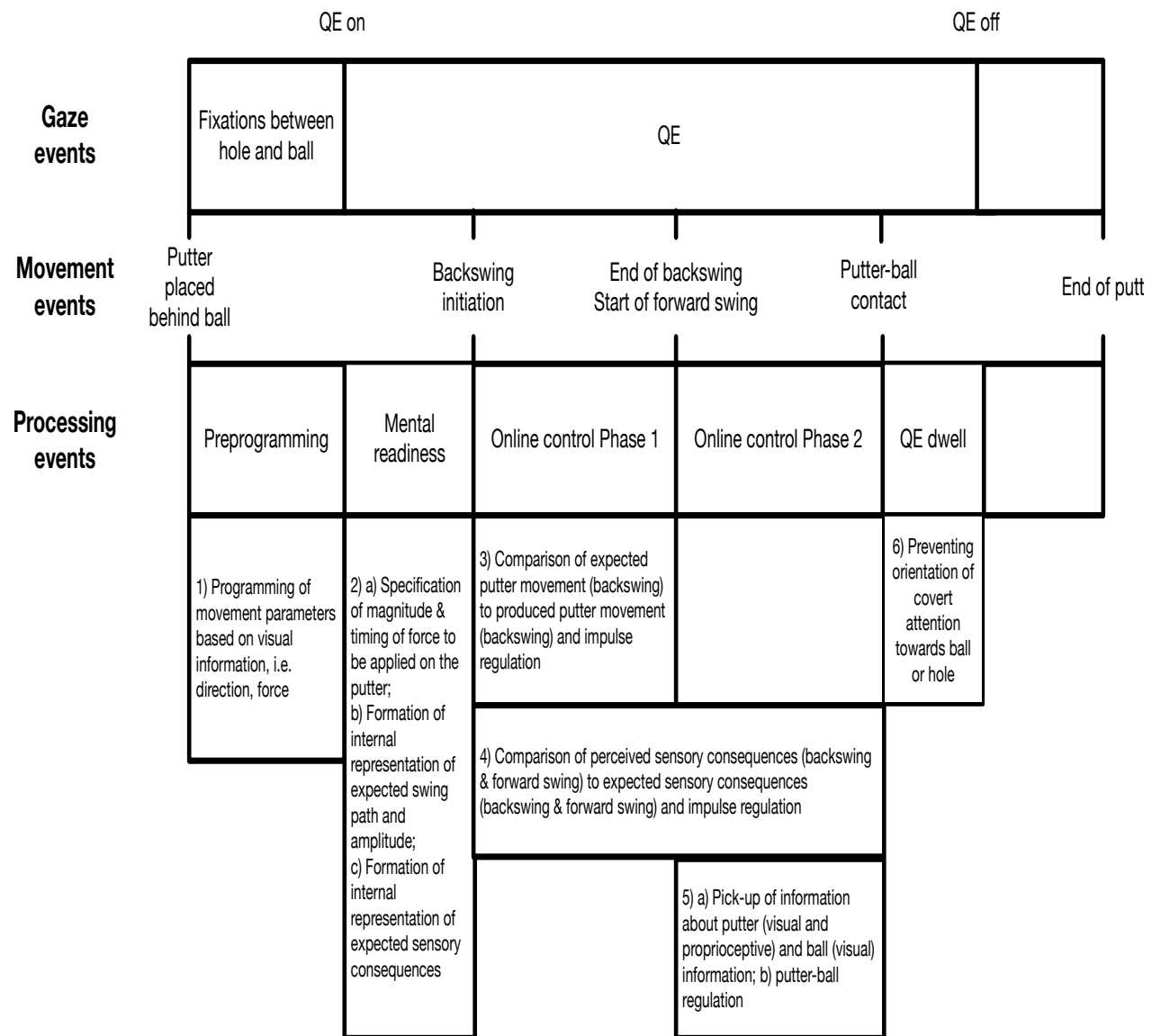
The first phase of the online control of movement requires the visual information about the targets to program upcoming movement and this pre-programmed

movement is stored in the central nervous system for future referencing during the execution of the movement (e.g., Evarts, 1973; Teuber & Mishkin, 1954; von Holst, 1954). Previous QE studies have suggested that QE provides a pre-programming function to help set the parameters for performance (Vickers, 1996, Williams et al. 2002), however I have suggested in Chapter 2 that pre-programming may occur earlier in the pre-shot routine (while fixating between the hole and the ball). Our instructions to the Front group was to have fixations between the hole and the ball before the last fixation on the paper ball and this resulted in no significant difference in accuracy compared with the Ball group. This might be the result of accurate (and sufficient) information for pre-programming before it is integrated into a movement pattern during the final (QE) fixation. In study 4, I divided QE into three different phases, where I assumed that pre-programming occurred prior to the initiation of backswing. However this period might have been used as the time to achieve a state of mental readiness before the execution of putt (Singer, 2000) rather than simply reflecting pre-programming.

According to Elliott et al.'s model, after this period of programming the backswing (impulse control) will initiate. The first phase of online control (backswing) will be compared with efferent copy via visual and proprioceptive feedback. When differences are detected between the plan and subsequent efferent feedback, online correction of movement will occur to adjust the putter trajectory and position. The second phase of online control (forward swing) requires constant visual information (QE) about the target (ball) in order to manoeuvre the putter-head which might have spatial discrepancy with the ball.

This spatial discrepancy could be accentuated under heightened anxiety, which has been shown to affect movement kinematics (Causer et al., 2011a). Based on the visual feedback of both the ball and the putter-head, continuous correction of putter-head occurs to achieve accurate putter-ball contact (as discussed in Chapter 3).

In Chapter 4, it was shown that anxiety causes early QE offset leading to deterioration in performance. According to the two-component model (Woodworth, 1899), the elimination of visual information during the homing phase of the movement should increase error. Although performers could still correct the errors in the putter-head movement based on their proprioceptive feedback, it is not as accurate as correction based on visual feedback (Carlton, 1981, 1992; Heath, 2005). This reflects why it was shown that the putting accuracy dropped when visual information during the putting action was disrupted in Chapter 3. QE provides visual information that helps continuous adjustment of putter movement until contact with the ball (Craig et al., 2000). This is in line with studies that have tested goal-directed aiming tasks without visual information about the target (for a review, see Elliott et al., 2010). Therefore the results of this thesis support multiple-process models of limb control and also show that this model can be applied to sports settings. Figure 5 represents hypothesized multiple processing events associated with golf putting, which is based on result from this thesis and Elliott et al.'s (2010) figure.



*Figure 5. Hypothesised multiple processing events associated with single golf putt. QE provides visual information necessary for movement correction during online control phase 1 & 2.*

There are also practical implications for the result of this thesis. First, there may be practical reasons for adopting audio-aid training of QE for golfers (Chapter 2). An audio recording can be saved to a portable MP3 player or smart phone so is practical to use during putting practice. Also, many researchers have suggested that imagined and actual movements at both behavioural and neural levels are

similar (Guillot & Collet, 2005) therefore imagery of putting practice with QE instruction may have similar impact compared to actual practice. In this regard, golfers would be able to train QE without constraints of time and location to improve their QE duration and potentially, subsequent putting performance. Future applied research could explore these potential benefits.

Second, it has been widely accepted by golf coaches and players that keeping an eye on the ball is important for the golf putting accuracy, especially from short distance. However it has been difficult to provide explanation, based on the scientific evidence, why golfer should keep an eye on the ball (or at least stationary) during the swing. The results of Chapter 3 and 4 suggest that steady fixation (QE) on the ball during the swing provides online control of putting movement; therefore golf coaches could use this scientific evidence to teach their students why it is important to keep an eye on the ball during the putter swing.

Finally, dividing QE into two components, as we did in Chapter 4 (i.e. pre-programming and online control) may have useful practical implications for golf coaches. This could be used as diagnosing tool to examine which component of QE the golfer is lacking. Ideally, an eye tracker would be required to capture eye data; however, as such technology may not be available to most coaches, a putting 'box' (equipped with LCD glass and infrared sensor) similar to the one we used in Chapter 3 could be utilised. If a golfer is performing poorly due to having reduced pre-programming then putting without early component of QE (without early visual information) will result in similar accuracy compared to when full vision is available. Similarly, a golfer who is poorer at online control

will struggle when late information is impaired. With this information golf coaches could develop tailored training regimes which aim to improve the area of weakness.

## **5.2. Limitations and Directions for Future Research**

The major limitation of this thesis was that relatively low sample sizes were used in the training studies (although these were similar as those used in previous QE training studies – Vine & Wilson, 2010, 2011). Future research which wishes to replicate or improve these studies should aim to recruit more participants to increase statistical power. Another limitation in the training studies is that we have only focused on the final QE fixation rather than the entire visual routine. An examination of the entire visual routine might be more informative in understanding the role of pre-programming in tasks such as golf putting. Therefore future studies should seek to unpick the relative importance of earlier fixations and the final QE fixation, in order to more fully explain the effect of QE training.

It is also a limitation of the current thesis that various distances were not adopted during retention and pressure tests. As players have to putt from different distances during a round of golf it might be important to assess various lengths of putts in transfer conditions. Recently, a Golf Australia Putting Test (GAPT) was developed which aimed to evaluate putting skills (Robertson, Gupta, Kremer, & Burnett, 2014). GAPT uses 6 putts from 6 different length putts with more points rewarded for holing longer putts. Future training studies could perhaps adopt GAPT to obtain additional performance data on top of mean radial errors to improve the ecological validity of laboratory based



training.

There are limitations in Chapter 4, in that anxiety and performance were not measured to the same level of sensitivity as the QE measures. Anxiety was not measured for every putt and we did not take a measure of performance error on the final (missed) putt (which would have enabled us to regress QE duration on performance). It is also a limitation of Chapter 4 that putter-head movement kinematics were not measured. Therefore we were not able to measure movement variability during early and late phases of the putt. However, considering the nature of the study design where the participants were competing in a shootout competition using their own putter, it was not possible to use the putter with a pre-attached accelerometer. Also Chapter 3 in this thesis and other studies investigated the effect of kinematics of putter movement did not show unequivocal and consistent patterns – perhaps supporting comments that putting kinematics may have limited influence on putting accuracy (Karlsen et al., 2008).

An important consideration for research examining the visual attention (gaze) of participants is the degree to which visual overt attention is representative of covert attention. Neuroscience research suggests that a shift in gaze invariably predicts a shift in attention (Corbetta, 1998) and that it is difficult to shift the point of gaze without shifting attention (Henderson, 2003; Henderson & Hollingworth, 1999). However, it is possible that covert attention could shift (e.g., inwardly) while overt attention, as measured by QE, remains fixed. Future research should consider adopting direct cortical measures of attentional control to assess potential dissociations in the orientation of overt and covert

attention (Vine et al., 2014).

### **5.3. Final conclusion**

In the last 20 years, the QE has gained growing attention among researchers investigating aiming tasks and has become accepted within the literature as a measure of optimal attentional control (Vine & Wilson, 2010). This thesis attempted to explore how QE works to support skill learning and performance under pressure. The finding of this thesis corroborates the efficacy of QE training. However these benefits of QE could be achieved regardless of duration and location of final fixation. The overriding finding of this research was that the duration and location of final fixation does not influence learning and robust performance under pressure. The well-researched benefits of an external focus of attention (e.g., Wulf, 2013) might explain why all QE training instructions were beneficial. Both the occlusion paradigm Study (Chapter 3) and putting shootout design (Chapter 4) adopted in the current thesis suggest that there may be too much emphasis placed on just the duration of the final (QE) fixation rather than its timing. The timing of the QE, to keep the fixation through unfolding of movement to ensure precise online control, seems to be a strong candidate for how QE exerts positive effects on performance.

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## **Appendix 1. Informed consent form for study 1**



### **The influence of manipulations of gaze location and duration on golfer's putting performance.**

#### **INFORMED CONSENT FORM FOR PARTICIPANTS**

I have read and understood the Information Sheet concerning this project, and all my questions have been answered satisfactorily. I understand that I am free to request further information at any stage,

I understand that:

1. My participation in the project is entirely voluntary;
2. I am free to withdraw from the project at any time without any disadvantage;
3. The data will be destroyed at the conclusion of the project, but any raw data on which the results of the project depend on will be retained in secure storage;
4. In the case of publication of collected data my anonymity will be preserved;

I agree to take part in this project.

.....  
(Signature of participant)

.....  
(Date)

This project has been reviewed and approved by the Ethics Committee  
of the School of Sport and Health Sciences

## **Appendix 2. Informed consent form for study 2**



### **The influence of manipulation of visual information on golfer's putting performance.**

#### **Informed consent form for participants**

I have read and understood the Information Sheet concerning the study, and all my questions have been answered satisfactorily. I understand that I am free to request further information at any stage.

I understand that:

1. My participation in the study is entirely voluntary
2. I am free to withdraw from the project at any time without any disadvantage
3. The data will be destroyed at the conclusion of the project, but any raw data on which the study depend on will be retained in secure storage
4. In the case of publication of collected data my anonymity will be persevered

I give informed consent to participate in this study.

.....  
(Signature)

.....  
(Date)

This project has been reviewed and approved by the Ethics Committee of the  
School of Sport and Health Science

### **Appendix 3. Informed consent form for study 3**



#### **The influence of anxiety on gaze control behaviors during pressurized putting task.**

#### **INFORMED CONSENT FORM FOR PARTICIPANTS**

I have read and understood the Information Sheet concerning this project, and all my questions have been answered satisfactorily. I understand that I am free to request further information at any stage,

I understand that:

1. My participation in the project is entirely voluntary;
2. I am free to withdraw from the project at any time without any disadvantage;
3. The data will be destroyed at the conclusion of the project, but any raw data on which the results of the project depend on will be retained in secure storage;
4. In the case of publication of collected data my anonymity will be preserved;

I agree to take part in this project.

.....  
(Signature of participant)

.....  
(Date)

This project has been reviewed and approved by the Ethics Committee  
of the School of Sport and Health Sciences

## **Appendix 4. Information sheet for study 1**



### **What affects do manipulations of gaze location and duration have on golfer's putting performance?**

#### **INFORMATION SHEET FOR PARTICIPANTS**

Thank you for showing an interest in this project. Please read this information sheet carefully before deciding whether or not to participate. If you decide to participate, I thank you in advance for the time and effort you have decided to devote to our investigation. If you decide not to take part, there will be no disadvantage to you of any kind and I thank you for considering my request.

#### **What is the aim of the project?**

The purpose of this research is to assess the effects of manipulation of golfer's visual attentional control, i.e. location and duration. Visual attentional control is one of major factor that underlies highly skilled performance of putting. The aim of this project is to find out whether manipulations of location and duration of golfer's attentional control have impact on golfer's putting performance.

#### **What types of participants are needed?**

We are looking for participants of any age with little or no experience in golf. To take part in the study you should be in good health, and be free of any sports or other injuries, which might make it difficult for you to carry out golf putting.

## **Appendix 5. Information sheet for study**



### **Visual orientation and putting performance**

#### **Information sheet for participants**

Thank you for showing an interest in this study. Please read this information sheet carefully before deciding whether or not to participate.

#### **What is the aim of the study?**

The QE, last fixation towards golf ball before initiation of backswing, is known to underlies highly skill of golf putting performance. In fact, one studies found that putter movement is only minor factor in successful putting performance. The aim of this study is to examine whether manipulations in timing of golfer's visual information have an impact on golfer's putting performance using an occlusion method.

#### **What is involved in the study?**

If you agree to participate you will be asked to attend a single testing session, which should last less than an hour. Prior to putting you will be asked to complete 3 questions questionnaire regarding how you feel. You will wear an eye tracker which reflects where your gaze is oriented to. You will perform total 18 putts.

#### **What types of participants are needed?**

We are looking for participants with handicap of 10 or below. To take part in the study you should be in good health and free from any sports or other injuries, which might make it difficult for you to carry out the golf putting.

#### **Any questions?**

If you have any questions, please do not hesitate to ask.

## **Appendix 6. Information sheet for study**



### **What affects does anxiety have on golfer's visual attentional control?**

#### **INFORMATION SHEET FOR PARTICIPANTS**

Thank you for showing an interest in this project. Please read this information sheet carefully before deciding whether or not to participate. If you decide to participate, I thank you in advance for the time and effort you have decided to devote to our investigation. If you decide not to take part, there will be no disadvantage to you of any kind and I thank you for considering my request.

#### **What is the aim of the project?**

The purpose of this research is to assess the effects of anxiety on golfer's visual attentional control. Visual attentional control is one of major factor that underlies highly skilled performance of putting. The aim of this project is to find out whether anxiety has adverse effect on golfer's visual attentional control during putting shootout.

#### **What types of participants are needed?**

I am looking for golfers of any age with handicap of 6 or less. To take part in the study you should be in good health, and be free of any sports or other injuries which might make it difficult for you to carry out golf putting.

## **Appendix 7. The Mental Readiness Form (MRF-3; Krane, 1994)**

The 3 questions below are designed to assess your performance state. Please indicate one number on each scale that you feel represents most closely how you feel **RIGHT NOW**.

3) My thoughts are:

1	2	3	4	5	6	7	8	9	10	11
---	---	---	---	---	---	---	---	---	----	----

**NOT WORRIED**

**WORRIED**

2) My body feels:

1	2	3	4	5	6	7	8	9	10	11
---	---	---	---	---	---	---	---	---	----	----

**NOT TENSE**

**TENSE**

1) I am feeling:

1	2	3	4	5	6	7	8	9	10	11
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**NOT CONFIDENT**

**CONFIDENT**